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AN EVALUATION IN A MODERN WIND TUNNEL
OF THE TRANSONIC ADAPTIVE WALL ADJUSTMENT
STRATEGY DEVELOPED BY NPL IN THE 1940's

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SUMMARY

The first documented wind tunnel employing a flexible walled test section for the purpose of eliminating wall interference was constructed in England by the National Physical Laboratory (NPL) during the late 1930's. The tunnel was transonic and designed for two-dimensional testing. In an attempt to eliminate the top and bottom wall interference effects on the model NPL developed a strategy to adjust two flexible walls to streamlined shapes. This report covers an evaluation of the NPL wall adjustment strategy in a modern wind tunnel, namely the Transonic Self-Streamlining Wind Tunnel (TSWT) at the University of Southampton, England. The evaluation took the form of performance comparisons with other modern strategies which have been developed for use in, and proven in, the TSWT.

The severity of wall interference is a function of, amongst other things, the proximity of the walls to the model which can be expressed, for convenience, as a ratio of test section height to model chord. For the early NPL tests the ratio was around 3.5, whereas in this evaluation it was 1.5, rendering this evaluation a more severe test of the effectiveness of the NPL strategy than the environment for which it was developed. Despite this fact, and the fact that by its nature the wall contours predicted by the NPL strategy only approximate to streamlines, the resulting model data over a wide range of test conditions, compared favourably with that obtained when wall streamlining was governed by the other proven strategies. Hence over this range of conditions, that is a range of Mach number and angle of incidence, wall streamlining according to the NPL strategy resulted in a near interference-free test environment. The only significant disadvantage of the NPL strategy within the applicable test regime, was the number and the magnitudes of wall adjustments necessary during the streamlining process, both of which are somewhat higher than the norm for modern predictive strategies.

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1. INTRODUCTION

The undesirable effects of wall interferences have been a problem as long as there have been wind tunnels. The need for improved test environments for wind tunnel model tests has long been apparent from disparities between tunnel and flight data. A post-test analysis of measured data and application of corrections is often unsatisfactory, particularly for large models in transonic and high incidence test regimes. In the most severe cases, the test section flow past the model is distorted to such an extent that the measurement is not correctable. In principle, boundary effects can be minimised by testing smaller models in larger tunnels, but reduction of model size reduces test accuracy and Reynolds number, whereas the alternative of increasing the tunnel dimensions substantially increases the facility cost and power consumption.

An attractive alternative is the adaptive wall wind tunnel, in which wall interference is either eliminated or significantly reduced by actively adapting the flow near the boundaries of the test section to match that of a free flowfield. In most cases adaptive test sections are '*self-streamlining*' in that the process of matching the shape of the test flowfield to the free flowfield (a process referred to as streamlining) is made by reference to the test section alone, independent of any knowledge of the model or the flow around it. Two distinctly different adaptive wall testing techniques have evolved. One is a development of the existing ventilated wall technique, employing the new feature of controlled distribution of out-flow and in-flow through the walls between the test section and a finite number of surrounding plenum chambers. The other technique utilises solid impervious flexible walls which control the test section flowfield by wall contouring. It is the latter technique which is considered in this report.

The idea of an accommodating wall to reduce wind tunnel interference is not new. The first documented wind tunnel employing a test section with adaptive walls was constructed in England by the National Physical Laboratory (NPL) during the late 1930's. NPL established an experimental procedure for the streamlining of solid flexible walls that is followed today, namely that the adjustment of the walls is based on measurements of wall static pressure (responding to the streamwise component of the disturbance velocity) and the local wall position (determining the flow angle).

This report details an evaluation of the transonic wall adjustment strategy (proposed, developed and used for streamlining by NPL) in a modern flexible walled wind tunnel; namely the Transonic Self-Streamlining Wind Tunnel (TSWT) at the University of Southampton, England. The evaluation took the form of performance comparisons with

other modern wall adjustment strategies which have been previously used and proven in the TSWT.

2. REDUCTION OF WALL INTERFERENCE BY WALL STREAMLINING

2.1 Principle of Wall Streamlining

If the walls of a test section could be adapted to follow any one of the infinite number of streamtubes that exist around a model in a free flowfield, then the test section boundary interference on the model would be eliminated. In practice the streamtube shape varies with reference Mach number, model shape and model incidence, therefore the test section walls need to be flexible.

In the case of a two-dimensional model in an infinite flowfield as shown on Figure 1, the streamtube can be regarded as bounded (above and below) by a pair of streamlines. Therefore, only two of the test section walls need be contoured, and then only in single curvature. The wall boundary interference effects at the model are eliminated when the two flexible walls follow any two streamlines (one above and one below the model), at which condition the walls are termed '*streamlined*'. As also shown on Figure 1 the flowfield can be divided into three portions:

- 1) An imaginary portion extending to infinity above the test section - I1.
- 2) A real portion within the test section - R.
- 3) An imaginary portion extending to infinity below the test section - I2.

When the walls are streamlined, there will be no pressure imbalance across the two boundaries between the real and imaginary flowfields (i.e. the wall loading is zero).

2.2 Measures of Wall Streamlining Quality

It must be recognised that zero loading is a practical impossibility and therefore some measures of acceptable levels of loading, or their consequences, must be established. One measure of wall streamlining quality may be determined from the wall loadings given by the differences between the static pressures measured at the flexible walls inside the test section and external static pressures on the outside of the walls. The external pressures are derived during computations of the imaginary flowfields which extend outwards from each flexible wall to infinity. The contour which is used as the boundary of the imaginary flowfields is not the physical shape of the wall, but an effective shape, called the effective aerodynamic wall contour. These effective aerodynamic contours allow for the displacement thickness of the flexible wall boundary layers (δ^*). Past

experience^{1,2,3} has shown that for reference speeds below Mach 0.85 an allowance for the variations of δ^* on the flexible walls, caused by the presence of the model, need not be made. In practice, therefore, the effective aerodynamic contour is usually the physical wall contour referenced to the appropriate aerodynamically straight contour.* Provided that the effective aerodynamic contour does not penetrate the wake or boundary layer of the model an inviscid solution to the imaginary flowfields is possible and proper. It follows that the imaginary flowfields will be less complex than the real flowfield close to the model, and the accuracy of the imaginary flowfield computations will always be more reliable than theoretical estimates of model performance, whatever the current state of the art. An accurate prediction of the external wall pressures given by the imaginary flowfield computations is necessary for the correct determination of wall streamlining quality.

Wall loading is evidence of wall interference; if the real (test section) and external pressures (or corresponding velocities) differ at any point along a wall then the wall is loaded at that point and the line followed by the wall is not that of a streamline in the infinite flowfield. In practice, the loading will be finite as the flexible walls can only be positioned within some tolerance band set by experimental and theoretical features of the system. As a matter of policy the flexible walls of the TSWT are contoured (according to several strategies) to eliminate as far as is feasible the top and bottom wall loadings consistent with an acceptable number of streamlining iterations.**

The differences in pressure across a wall has been introduced as one measure of the quality of wall streamlining. At a point along a wall the apparent pressure difference, having in general a true component but also an erroneous component because of measurement and computational errors, is converted into a pressure difference coefficient and used as a measure of the local wall loading. Coefficient values are available at each jack position, but the practice has long been adopted of evaluating an average value for each wall, given the symbol E . Formally, E is the average of the modulus of the set of pressure difference coefficients determined at each jack along a wall. Experience^{2,4} has shown that for the TSWT satisfactory streamlines exist when the value of E is less than 0.01 on both walls.

* For definition of aerodynamically straight see Section 6.

** Satisfactory streamlines are only achieved after a number of streamlining iterations. One streamlining iteration comprises of setting walls to known shapes, measuring wall pressures, assessing the quality of wall streamlining and computing new wall contours.

After each streamlining iteration residual interference effects at the model due to the remaining wall loading are calculated using linearised theory², providing more measures of the quality of wall streamlining. For convenience the residual interference effects are expressed in terms of:-

- 1) Induced angle of incidence at the aerofoil leading edge.
- 2) Induced camber.
- 3) Streamwise velocity error at the quarter chord point of the aerofoil expressed as an error in pressure coefficient.

However, for the purpose of this report wall streamlining quality is solely assessed in terms of E .

Past experience² has shown that when the walls are streamlined ($E < 0.01$ on both walls), none of the three components of the residual interference alone induce an error in C_L greater than about 0.008. Typically this limit in C_L results from maximum residual interference effects of:-

$$\alpha = 0.015 \text{ degree}$$

$$\text{Camber} = 0.07 \text{ degree}$$

$$C_p = 0.007$$

3. EARLY FLEXIBLE WALLED TEST SECTION DEVELOPMENT AT THE NATIONAL PHYSICAL LABORATORY

(NPL - Teddington, Middlesex, England)

In the 1930's the technology to deal with test section boundary interference developed in three major directions. In one direction, the '*classical*' theory predicting wall interference corrections was systematically expanded to include more realistic aircraft and test section configurations. The second direction (which during the 1930's appears to have only been considered for low speed testing) was the application of the notion of ventilation as a means of minimising wall interference. This followed the observation of opposite signs of the corrections applied to open test sections and closed test sections. The third direction was related to a pressing practical problem; namely choking in high speed wind tunnels. During the 1930's the term high speed meant velocities approaching that of sound. Choking is the result of massive blockage-induced wall interference and was a real barrier to the advancement of test speeds and therefore to the understanding of transonic flows.

In 1937 Bailey and Wood⁵ of NPL reported that the effect of modifying the longitudinal profile of a test section, to compensate for the presence of the model, was to raise the speed at which choking occurred. The work was carried out in an induced-flow tunnel having a test section of 6 inch x 3 inch in cross-section and 6 inches in length (subsequently lengthened to 9 inches). Adjustments to the longitudinal profile of the test section were made by the insertion of liners. Since the tunnel profile varied for each test condition Bailey and Wood suggested it would be convenient to use adjustable flexible walls on the sides of the tunnel parallel to the axis of the aerofoil. This is thought to be the first reference relating to the use of flexible walls in wind tunnel test sections. Bailey and Wood further postulated that the flexible walls could be given such a profile that free flowfield conditions could be simulated; at the time they believed, incorrectly, that such a profile was one that gave constant static pressure, equal to the reference value, along the centrelines of the flexible walls.

In order to determine the feasibility of using flexible walls the 6 inch x 3 inch Tunnel was modified. A schematic layout of the tunnel, showing its configuration after the modifications, is shown on Figure 2. The author believes this to be the first documented wind tunnel employing a test section with adaptive walls.* The test section

* This tunnel was still in operational service at the University of Southampton in 1957⁶.

was of rectangular shape, a nominal 5 inch x 2 inch in cross-section, the narrower walls being flexible along their entire length of 9 inches. Each flexible wall, manufactured from spring steel plate, was adjusted by six micrometer screws spaced at 1.5 inch intervals. Investigations were carried out in three major areas: the reduction of interference between test section and model; the control of tunnel speed by a downstream contraction; and into the length of test section necessary for satisfactory upstream and downstream conditions to be reached. The test data, reported by Bailey and Wood⁷ in 1938, demonstrated the elimination of wake blockage in two-dimensional model tests at various angles of incidence up to a reference Mach number of 0.89. Thus, Bailey and Wood appear to have been the originators of the concept of adaptive walled test sections.

Utilising the valuable experience gained with the 5 inch x 2 inch Tunnel the High-speed Rectangular Tunnel (NPL Tunnel) was designed in 1937 and given its initial run in May 1941. The test section of the NPL Tunnel was 20 inch x 8 inch in cross-section, the narrower walls were flexible and 48.5 inches in length. A schematic layout of the NPL Tunnel is shown on Figure 3 (for further details of the NPL Tunnel see Section 4 and References 8, 9 and 10). The flexible walls were adjusted to streamlined contours according to a transonic strategy developed by NPL (for details of the strategy see Section 7.3), which utilised only the tunnel reference flow conditions and the available 'wall data'*. Hence the NPL Tunnel was the first truly self-streamlining wind tunnel. The tunnel employed the most advanced flexible walled test section developed by NPL and enabled valuable investigations into test section boundary interference at compressible speeds. The tunnel remained in service for about fifteen years. Lock and Beavan⁹ concluded that for two-dimensional tests reliable wall interference-free data from the NPL Tunnel could be attained for reference speeds up to about Mach 0.85; only when the model shock had just extended to one flexible wall of the test section were the tunnel results invalidated. They also concluded that a model of 5 inch chord (representing a test section height to chord ratio of approximately 3.5) was about as large as should normally be used, and in this case lift could be estimated from the static pressures measured on the streamlined walls.

At one stage NPL proposed to construct a wind tunnel with a flexible walled test section of 12ft x 6ft in cross-section and 48ft in length. It was thought necessary that the scheme be put to the test on a larger scale than the existing NPL Tunnel to aid the design

* 'Wall data' for flexible walled test sections consists of wall geometry and static pressure distributions along the centrelines of the flexible walls.

of the two-dimensional test section of the proposed new tunnel. This led to the installation of adaptive flexible walls (4ft wide and 13ft long), constructed from plywood, in the NPL 4ft No.2 Tunnel. A schematic layout of the test section is shown on Figure 4. Self-adjusting flexible fairings were used to provide a smooth transition between the flexible walls and the original walls of the test section. The tunnel was not self-streamlining because in this case the flexible walls were adjusted (by 12 jacks on each wall) to contours that followed calculated streamlined shapes¹¹. In 1944 Preston, Sweeting and Cox¹² reported that wall interference-free conditions had been established in the tunnel and that no operational difficulties existed with large scale flexible walled test sections. Furthermore, they suggested that wall jacks driven by electric motors should be considered as a possible means to reduce the time and labour associated with wall setting. This scheme is used in the majority of all modern flexible walled test sections. However the proposed large scale NPL flexible walled wind tunnel was never constructed.

In 1946 NPL proposed to construct a new high-speed wind tunnel of closed circuit design with a test section of 18 inch x 14 inch in cross-section. The narrower walls were to have been adjustable with a range of movement adequate for both the reduction of wall interference at subsonic speeds, and the formation of a diffuser for supersonic operation. Although the design of the proposed tunnel appears to have been completed¹⁰, construction never commenced.

Research into flexible walled test sections at NPL was initially undertaken because of the need to relieve test section choking; the most severe consequence of wall boundary interference. Parallel research efforts which explored, in turn, several other approaches to obtaining high speed interference-free test data (including drop tests, the transonic bump, and small models on aircraft wings), finally settled on test sections with ventilation. The ventilated-wall geometry (developed initially for low speed testing) alleviated the choking problem at high speeds and reduced other effects of wall interference without unacceptable power losses. The ventilated test sections proved to be more practical in operation by eliminating the long wall setting times and therefore research into adaptive flexible walled test sections at NPL ceased* and ventilated test

* It should be noted that in 1945 a 9ft high-speed wind tunnel employing a flexible walled test section was discovered in West Germany (at Ottobrunn, near Munich). The only documentation relating to the tunnel detected by the author may be found in References 13, 14 and 15.

sections became universally accepted for transonic testing. However, in moving to the ventilated design at least two features of the test environment deteriorated; tunnel drive power increased, and flow quality was reduced. The ventilated walls were *passive* in the sense that there was no overt control of the flow through the walls. The absence of a rational interference assessment method for ventilated test sections (due to the nonlinear nature of the transonic flow equations, the complex wall geometries and the ill-defined boundary conditions which they produce) was one of the reasons which led to the renewed interest in adaptive test sections during the early 1970's.

4. DESCRIPTION OF THE NPL HIGH-SPEED RECTANGULAR TUNNEL

The NPL High-speed Rectangular Tunnel (NPL Tunnel) operated with stagnation conditions of ambient pressure and temperature. At first the NPL Tunnel was of the open circuit type but in June 1945 a return leg was fitted. The induced-flow was driven by compressed air through an injector (of similar design to that employed in the TSWT) downstream of the test section. Tunnel run-time at the higher speeds (around Mach 0.9) was limited to about 4 minutes. Screens of coarse wire and muslin (later replaced by fine copper gauzes) were mounted in the intake box for flow smoothing. Prior to the installation of the return leg condensation of moisture in the test section flow was often experienced at reference speeds above Mach 0.6.

A schematic layout of the test section of the NPL Tunnel is shown on Figure 3. The test section was of rectangular shape, a nominal 20 inch x 8 inch in cross-section, the narrower walls being impervious and flexible along their entire length of 48.5 inches. The flexible walls were made from 0.020 inch spring steel and were adjusted in single curvature by 19 micrometers on each wall, the last two downstream micrometers on each wall controlling an adjustable throat, as shown on Figure 3. Hence, the streamlined portion of the test section effectively extended from the first to the seventeenth micrometer (giving 37.7 inches of streamlined length) on each wall. In the vicinity of the model micrometers were spaced at 1.5 inch intervals, while upstream and downstream of the model micrometer spacing increased to 3 inches. Static pressures were measured on the centrelines of the flexible walls, via 0.02 inch diameter tappings and multitube manometers, at all micrometer positions and at a few points in the vicinity of the downstream throat. The tunnel reference speed was deduced from the static pressure measured on one of the flexible walls 8.5 inches ahead of the leading edge of the standard 5 inch chord model, as shown on Figure 3. The 20 inch sidewalls, rigid and parallel, were provided with glass windows which supported the model, enabling flow visualisation near the model.

The NPL Tunnel enabled valuable investigations to proceed into the alleviation of test section boundary interference at compressible speeds⁸⁻¹⁰. These investigations employed several two-dimensional models: EC 1250 sections of 2, 5 and 12 inch chord; a NACA 2278 section of 5 inch chord; and a Mustang section of 5 inch chord, have been reported. For all models a number of pitot traverse measurements of the profile drag were made. During the investigations the highest attained reference speed was Mach 0.955 with an empty test section and Mach 0.94 with a model installed in the test section. The

NPL Tunnel was also run empty at a low supersonic speed (Mach 1.15) by adjusting the flexible walls to form a convergent-divergent nozzle.

5. DESCRIPTION OF THE TRANSONIC SELF-STREAMLINING WIND TUNNEL

5.1 Wind Tunnel Layout

A schematic layout of the wind tunnel is shown on Figure 5. The tunnel has a closed circuit with stagnation conditions of ambient pressure and temperature. The induced-flow is driven by dried compressed air through an injector downstream of the test section, as shown on Figure 6. Mach number in the tunnel may be varied continuously from low subsonic to low supersonic by adjustments to inducing air pressure and test section wall contours. Tunnel run-time varies from near infinity at low speeds to a maximum of about two minutes at high speeds. Inducing air pressure control is handled by a pneumatic Fisher control valve system which allows the rapid setting-up of reference Mach number and provides good stabilisation of Mach number despite the falling compressed air reservoir pressure experienced, particularly during a high speed run. There are a series of screens mounted in the settling chamber upstream of the contraction for flow smoothing. The tunnel cross-section at the screens is 36 inches square, therefore with the test section at its nominal 6 inch depth the contraction ratio is 36:1. In the return leg of the tunnel circuit there is an air exhaust to maintain ambient conditions and for safety reasons there are two blow-off valves.

5.2 Flexible Walled Test Section

A schematic layout of the TSWT test section is shown on Figure 6. The layout represents what is regarded as a near optimum design of a flexible walled test section.

The test section is 6 inches square in cross-section at the upstream end, with parallel rigid non-porous sidewalls throughout. The impervious top and bottom flexible walls, 44 inches in length, are anchored at their upstream ends to the fixed contraction and adjusted in single curvature by twenty motor-driven screw jacks on each wall. Wall shape is monitored at all jack positions. The 20th and last downstream jack of each wall controls the free end of the flexible wall in a sliding joint coupled to a variable diffuser. Hence, the streamlined portion of the test section effectively extends from jack 1 to jack 19 (giving 38 inches of streamlined length) on each wall. Jacks 20 are available for Mach control, however as no inconvenient fluctuations in reference Mach number are experienced³ at speeds below about Mach 0.9, no downstream throat was formed during the tests presently under discussion.

The flexible walls are made from woven man-made fibre (Terylene) laminate. Presumably they deform between jacks to contours dictated by their structural properties, rather than following streamlines. Since the wall pressure loading and the streamline curvature both peak near the model, jacks are pitched closer together in this region than elsewhere. There are eight closely grouped jacks per wall near the model with a spacing of 1 inch, while upstream and downstream of the model the jack spacing increases to 3 inches maximum, as shown on Figure 6. The flexible walls are 0.2 inches thick at their ends where the jack pitch is large, with a central portion de-laminated to a thickness of 0.1 inches coinciding with the closely grouped jacks.

The two-dimensional model is mounted horizontally on glass windows integral with the rigid sidewalls, thereby allowing several flow visualisation techniques (e.g. schlieren photography). There is no provision for sidewall boundary layer control. The quarter chord point of the model is arranged to translate vertically with the change in angle of incidence to minimise wall curvature and help centralise the model between the walls in the presence of changing up and downwash. By mounting the model symmetrically in the streamlined portion of the test section the effects of the loading of the two ends of the test section largely cancel each other.¹⁶

As shown on Figure 6 a pitot rake is positioned on each flexible wall between jacks 19 and 20 to search for a potential flow core between the model wake and flexible wall boundary layers. Mixing of the model wake and wall boundary layer invalidates the underlying assumptions of wall streamlining.

The pressure data used in predicting the contours for two-dimensional interference-free flow comprises merely of the static pressure distributions along the flexible walls, and the tunnel reference Mach number. Static pressures are measured, via a Scanivalve and pressure transducers, on the centreline (and other stations) of both flexible walls at all jack positions, except at the last downstream jack of each wall (i.e. jacks 20). The tunnel reference Mach number (M_∞) is determined from a reference static pressure measured on the centre of one sidewall in the plane of the flexible wall anchor points, as shown on Figure 6, and the reference total pressure measured just downstream of the screens in the settling chamber. The length of the test section has been chosen¹⁶ so that the disturbance induced by the model in the streamwise component of flow is negligible at the reference static point.

5.3 The Model

The model used throughout this investigation was a NACA 0012-64 aerofoil of 4 inch chord and 6 inch span (see Table 1 and 2 for further details of the model). The same model has been used for the majority of all previous two-dimensional model tests in the tunnel and is constructed from stainless steel.

Each surface of the model has twenty-two static pressure tapings with five tapings grouped within the first 10% of the chord and the remainder spaced at approximately 5% chord intervals as shown in Table 2. The tapings on the upper surface are positioned along a chord line 2.25 inches from one sidewall. The tapings on the lower surface are positioned along a chord line 3.75 inches from the same sidewall. Hence, the sets of upper and lower tapings are displaced spanwise by 1.5 inches symmetrically about mid-span.

A grit transition band, approximately 0.1 inches wide, was applied to the upper and lower surfaces centered at the 5% chord position. Under some test conditions (M_∞ greater than about 0.7) the concentration of grit could be seen by schlieren pictures to produce weak shock waves near the leading edge. The weak shock waves affected the detailed shape of the pressure suction peak near the transition band.

The ratio of test section height to chord of 1.5 for these TSWT tests is much lower than normal for conventional two-dimensional testing. The standard height to chord ratio of tests in the NPL Tunnel was 3.5, hence it can be concluded that the present TSWT tests provide a much more severe streamlining environment than tests reported by NPL⁸⁻¹⁰.

No attempt was made to accurately align the model zero angular reference with the test section flow and therefore the quoted angles of incidence are merely nominal. However, care was taken in measuring the changes in angle of incidence which are estimated to be accurate to 0.1 degree.

6. AERODYNAMICALLY STRAIGHT WALL CONTOURS

The iterative process of contouring the flexible walls toward streamlines depends on the magnitude of the flow disturbances caused by the model within the test section, and also on computations of the imaginary flowfields extending from the flexible walls out to infinity. Both depend upon the displacements of the walls from straight. Therefore, a prerequisite for streamlining the walls around a model is the determination of the straight contours, at first sight a contradiction in terms which requires explanation. The aim of straight wall contours is to diverge the two flexible walls from geometrically straight, in order to absorb the growth of the displacement thickness of the boundary layers on all four walls of the empty test section. The diverging contours result in a constant indicated Mach number along the centrelines of the flexible walls of the empty test section, equal to the reference value. Wall contours derived in this way are described as '*aerodynamically straight*'.

The aerodynamically straight contours are functions of Reynolds number and Mach number. In the TSWT the two vary together because of the atmospheric stagnation conditions. Therefore, the variation of aerodynamically straight contours is, in principle, a continuous function of reference Mach number. However, it has been found^{17,18} that variations of the contours are a rather weak function of reference Mach number and it is adequate to determine only a few sets of aerodynamically straight contours and to designate each to a band of reference Mach number. The determination of aerodynamically straight contours in wind tunnels which have the provision for variable stagnation conditions would be a more complex procedure. When streamlining the flexible walls around a model it has become practice that wall displacements be referenced to the appropriate aerodynamically straight contours.

Aerodynamically straight contours were derived by adjusting the walls according to an old strategy (now referred to as the Imbalance wall adjustment strategy). This strategy uses the simple rule that, in subsonic flow, the Mach number at a point on the wall will be reduced by moving the wall locally away from the test section centreline, and vice-versa. The movement of a jack is made proportional to the difference between the local (wall centreline) and the reference Mach number. An aerodynamically straight streamlining cycle* typically comprises of not more than 10 streamlining iterations when initiated from walls set to geometrically straight.

* A streamlining cycle consists of a series of iterations bringing the walls to satisfactory wall contours.

The quality of aerodynamically straight streamlining in the TSWT is summarised by the standard deviation of the wall centreline Mach number errors measured at the first 18 jack positions on each wall. The standard deviations are weighted by the reference Mach number, and the quality of the streamlining of a pair of walls is then summarised by the average weighted standard deviation (σ_{av}) given by:-

$$\sigma_{av} = \frac{\sigma_T + \sigma_B}{2M_\infty}$$

where σ_T , σ_B are respectively the top and bottom wall standard deviations in measured Mach number from the reference value (M_∞).

7. DESCRIPTION OF WALL ADJUSTMENT STRATEGIES

The wall adjustment strategy (WAS) is a fundamental component of the self-streamlining process. The object of any strategy is to predict new wall contours which will eliminate wall loading and therefore eliminate the top and bottom wall interference present during the current run.* In practice wall streamlining is achieved by means of wall adjustments in iterative steps. The flexible walled test section itself, influenced by the flow disturbances generated by a model, provides all the information necessary for wall streamlining; hence the use of the descriptive phrase '*self-streamlining*'. The only information used in the two-dimensional streamlining process is the tunnel reference flow conditions and the wall data. The wall data consists of the wall geometry and the static pressure distributions along the centreline of the flexible walls. The wall adjustment strategies reported here make no assumption of prior knowledge of the aerodynamic behaviour of the model, neither are model measurements a necessary adjunct to the wall streamlining process.

The wall adjustment strategies investigated in this report are denoted by the following:-

- 1) WAS 1 - Predictive strategy used in routine two-dimensional testing in the TSWT.
- 2) TSP WAS - WAS 1 strategy but with a more recently derived imaginary flowfield computation (TSWT TSP code).**
- 3) NPL 1 WAS - NPL strategy used in two-dimensional testing in the NPL Tunnel during the 1940's.
- 4) NPL 2 WAS - Modification of the NPL strategy suggested by NPL.

* The word '*run*' is used here in the context of data gathering; a run is a period during which all pressures (and perhaps other data) are being gathered.

** See Section 7.2 for details of TSWT TSP code.

7.1 Predictive Wall Adjustment Strategy

Following the realisation that the simple Imbalance wall adjustment strategy (see Section 6 for details of the strategy) for contouring the flexible walls of two-dimensional test sections to streamlined contours was too slow for practical use¹, Judd proposed,^{16,19} developed and placed in service²⁰ the Predictive wall adjustment strategy (WAS 1). During the following years the strategy was further refined^{21,22} and extensively used and proven up to transonic speed.^{2,4,23-25} The strategy reduced by 75% or more the number of iterations required to bring the flexible walls to satisfactory contours, and therefore the tunnel run-time attributable to the streamlining process was significantly reduced. It has been demonstrated that the strategy works well in two-dimensional testing at any set of conditions up to those which result in the model's shock just extending to a streamlined wall (usually this would be the suction surface shock just extending to the nearest wall).

The strategy was first implemented in 1976 in work with a low speed flexible walled test section and is still used in routine two-dimensional testing in the TSWT. More recently the strategy has been utilised in the software which controls the flexible walls of the test section insert of the 0.3-m Transonic Cryogenic Tunnel at NASA Langley Research Center.

The strategy makes use of wall information in predicting new wall contours which will reduce the wall loading during the current run, and thereby reduce top and bottom wall interference, whilst simultaneously providing the external velocity distributions over the outsides of the new contours. Reference 26 gives a detailed description of the underlying aerodynamic theory which forms the basis of the strategy.

7.2 TSP Predictive Wall Adjustment Strategy

The nature of the imaginary flowfield computations embodied in the WAS 1 strategy limits the operational Mach number of the TSWT. At higher speeds supercritical flow extends *through* the walls when they are not straight, invalidating the linearised theory used to compute the imaginary flowfields. To permit the extension of two-dimensional testing to higher transonic speeds (where the channels over and under the model can both be choked) a major new development was necessary. This was the provision of a code to solve the mixed flows now in the imaginary flowfields. Software provided by RAE Farnborough (designed to predict two-dimensional irrotational flow past lifting aerofoils²⁷ by solving the Transonic Small Perturbation (TSP) equation) was

adapted for the prediction of the imaginary flowfields of the TSWT, in particular when containing mixed flows with weak shocks. Development, refinement and validation of the resulting code (TSWT TSP code) coupled with initial test experience gained in utilising the new code in the TSWT has been previously reported^{3,28} and therefore is not dealt with in this report. Initially it was expected that satisfactory TSWT TSP solutions would be obtained only when the reference Mach number was close to unity. However for TSWT applications it was found³ that in the subsonic band the TSWT TSP solutions compared favourably with those obtained by other available computational methods^{1,21,29}, even when the reference Mach number was as low as 0.4.

The TSP Predictive wall adjustment strategy (TSP WAS) was formed by replacing the imaginary flowfield computations of the WAS 1 strategy with the TSWT TSP code. In principle, and practice,³ the TSP strategy is capable of wall streamlining at test conditions where the shocks of the model intrude into the imaginary flowfields. However, for the conditions of the tests presented in this report the strategy happened only to be utilised at conditions where the imaginary flowfields were wholly subsonic.

Any discrepancies that may exist between the model data obtained when the walls were streamlined according to the TSP and WAS 1 strategies are solely due, within experimental limits, to the different computational methods used by the strategies in predicting the imaginary flowfields.

7.3 NPL Wall Adjustment Strategy

The transonic strategy proposed, developed and used by NPL^{9,10,14,30-33} in the 1940's for wall streamlining involved determining, experimentally, the wall contours that gave constant static pressure (hence constant Mach number) equal to the reference value along the centrelines of the flexible walls. These contours were derived with the model installed in the test section and for the purposes of this report are described as '*constant pressure*' contours. Such contours simulate open jet conditions and therefore still induce wall interference effects at the model. For wall streamlining, the flexible walls were then positioned to shapes between the constant pressure contours and the previously derived aerodynamically straight contours. The strategy was based on conclusions from a series of theoretical calculations of inviscid incompressible flows around simple two-dimensional models.^{9,10} In this theoretical work the model blockage was represented by a single doublet, the wake behind the model by a single source, and any lift by a point vortex. It

was found that the streamlined contours were everywhere roughly half-way between the constant pressure and aerodynamically straight contours.

The above described wall adjustment strategy employing the half-way setting factor (NPL 1 WAS) was used to streamline the flexible walls of the NPL Tunnel (see Section 4 for tunnel details). Difficulty was experienced in the NPL Tunnel in obtaining wall contours that gave constant static pressures, equal to the reference value, on both walls when lift was present. Therefore NPL adopted the practice of adjusting the flexible walls to contours that gave constant static pressures along the centrelines of the walls, but with the pressures differing on the two sides of the test section; the value of the difference depending on the magnitude of the lift present. The contours were derived experimentally by employing what we now term the Imbalance wall adjustment strategy*, as were the aerodynamically straight contours. The above mentioned NPL practice was not required when deriving constant pressure contours in the TSWT, as contours exhibiting constant static pressures equal to the reference value on both walls could be attained without difficulty. The problems experienced in deriving constant pressure contours in the NPL Tunnel may have been due to the reference pressure orifice being influenced by the disturbance caused by the lifting model, as the orifice was situated only 8.5 inches ahead of the leading edge of the standard 5 inch chord model. The fact that the reference orifice was located on one flexible wall further complicated the matter, since the orifice would also be influenced by the disturbance caused by wall movement.

Lock and Beavan⁹ suggested that the NPL strategy employing a setting factor of six-tenths towards the constant pressure contour (NPL 2 WAS) would be more *'nearly correct'* in the vicinity of the model than the previous half-way setting factor. They also suggested an additional calculated wall movement based on the estimated lift coefficient of the model. As far as the author is aware any tests utilising the new setting factor of sixth-tenths (NPL 2 WAS) and/or the extra wall movement to streamline the flexible walls of the NPL Tunnel have never been published.

The value of the setting factor between the constant pressure and aerodynamically straight contours may well be test section dependent. However the two setting factors suggested by NPL were expected to be sufficiently accurate for most test sections,³¹ therefore only these setting factors were used during the present evaluation of the NPL strategy in the TSWT.

* For details of the Imbalance wall adjustment strategy see Section 6.

8. TSWT TEST DATA

8.1 Test Conditions

The model was tested through a range of reference Mach numbers from 0.4 to 0.8 at three angles of incidence (nominally 0.5° , 2.0° and 4.0°). The model remained locked at one specific angle of incidence while the walls were streamlined through the Mach number band according to the various wall adjustment strategies, thereby reducing uncertainties in model incidence that might otherwise exist when making comparisons between the strategies. A greater range of test conditions was not possible primarily because the maximum jack movement of 1 inch (fixed by the wall position sensing device) limited the test range within which constant pressure contours could be derived in the TSWT. However the extent of the achieved test range was considered great enough to provide an interesting comparison of the wall adjustment strategies and a valid evaluation of the NPL strategy.

8.2 Test Programme

In tests aimed at wall streamlining at high reference Mach numbers, the conventional streamlining process (using the WAS 1 strategy) begins by first running a test at a Mach number below that which chokes the test section with the walls straight. The initial movements of the walls towards streamlines have a profound effect on the test section choking Mach number and for most conventional tests the streamlining cycle is usually able to continue at the required reference Mach number after the first iteration. The test sequence usually proceeds from one set of streamlined contours for one test condition to other test conditions and streamlined contours. The number of streamlining iterations for each test condition increases with the severity of the change in test conditions from one streamlining cycle to the next. The test programme is usually chosen to minimise tunnel run-time based on the general rules that in two-dimensional testing changes in wall contours with test conditions are small in the case of a Mach sweep, and, of course, are small if the change of angle of incidence is small. The walls need never be, and usually are not, re-set to straight during a test programme. However, for the tests presented in this report the streamlining cycle (governed by several strategies), whenever possible was initiated from aerodynamically straight wall contours for each test condition. Only when the test reference Mach number was greater than the straight wall choking value were the streamlined wall contours of the previous streamlining cycle used as a starting point for the next cycle. The test programme was designed to reduce uncertainties that might exist (due to different starting points of the streamlining process)

when making comparisons between the several wall adjustment strategies for each test condition, as opposed to minimising tunnel run-time.

8.3 Aerodynamically Straight Wall Contours

A prerequisite of all model tests in the TSWT (and the implementation of the NPL strategy) is the determination of aerodynamically straight contours (see Section 6 for details). Such contours have recently been derived following the installation of new flexible walls in the TSWT.

The achieved quality of aerodynamically straight streamlining is summarised in Table 3, whilst the wall Mach number distributions along the wall centrelines of the contours is shown on Figure 7. The wall displacements (referenced to geometrically straight) for aerodynamically straight contours E, which are typical, are shown on Figure 9.1.

8.4 Constant Pressure Wall Contours

One step in the NPL strategy is the determination of constant pressure wall contours. Constant pressure contours were routinely derived (within the limits discussed in Section 8.1) in the TSWT by adjusting the flexible walls according to the Imbalance strategy (see Section 6 for details of this strategy).

The quality of constant pressure streamlining of a pair of walls is again summarised by the average weighted standard deviation* value (σ_{av}). Wall adjustments were continued until no further reduction in the deviation value was experienced, the value typically lying in the band of 0.003 to 0.0055. The relationship between the wall movement (δy inches) and the desired change of local wall Mach number (δM) which was used for all wall adjustments was $\delta y/\delta M$ equal to 0.4 inches.

Satisfactory constant pressure contours were only reached after many streamlining iterations; the extreme was the 17 iterations necessary to derive contour D.3 when the streamlining cycle was initiated from walls set to aerodynamically straight contours. The number of iterations can be dramatically reduced by a well designed test programme, as discussed in Section 8.2. However, when deriving constant pressure contours in the future it may prove fruitful, in terms of the required number of iterations,

* See Section 6 for definition of average weighted standard deviation.

to employ the WAS 1 strategy but with the perturbations in the imaginary flowfields artificially set to zero. This method has been explored during which contour D.3 was re-defined (within satisfactory standards) from aerodynamically straight contours after only 9 iterations by employing the modified WAS 1 strategy.

The streamlining quality of constant pressure contours derived in the TSWT is summarised in Table 4, whilst the Mach number distributions along the centrelines of the walls for each of the contours are shown on Figures 8.1-8.3. The quality of the constant pressure contours does not match that achieved for aerodynamically straight contours, as can be seen by comparing Tables 3 and 4. The Mach number distributions indicate that further wall adjustments, localised near the model, may have led to an improved definition of constant pressure contours. However, it was concluded that the present contours were defined satisfactorily. Confidence is added by the fact that most contours (the exceptions are A.3 and B.3) satisfied the normal wall streamlining criteria ($E < 0.01$ on both walls) when the value of E was calculated by artificially setting the perturbations of the imaginary flowfields to zero (see Table 4). These artificial wall loading values (E^*) may be used as an alternative measure of the quality of constant pressure streamlining.

Typical constant pressure wall displacements (referenced to geometrically straight) are illustrated on Figures 9.1-9.3. As expected, the effects of increasing Mach number and model lift are to demand increased wall movement, particularly in the top wall. It is interesting to note that towards the downstream end of the test section the aerodynamically straight and constant pressure contours nearly coincide (i.e. discrepancies in total wall movement are not greater than 0.006 inches). This implies that the thickness of the model wake was small, therefore it may be deduced that under constant pressure contour conditions a shock induced separation of the model boundary layer did not occur for the test conditions investigated. When the walls were streamlined according to the TSP and WAS 1 strategies the total outward movement of the walls downstream of the model, in order to accommodate the model wake, was typically about 0.050 inches (as shown on Figures 13.1.2, 13.2.2, 13.3.2 and 13.4.2).

In experiments such as these where the reference Mach number is subsonic, the test section choking caused by the strong interference of straight walls is, by definition, overcome by contouring the walls to constant pressure contours. However, as the walls are far from streamlines* the model still suffers from wall interference effects. The

- * Constant pressure contours simulate open-jet conditions.

magnitude of one interference effect present with straight and constant pressure wall contours may be seen in Table 5 (a set of lift curve slopes) and by the lift-incidence data presented on Figures 15.1 - 15.3. At each Mach number the slopes given by the four streamlining strategies are in fair agreement with each other, except at Mach 0.8 where breakdown of the NPL strategy is evident (but this point is discussed further in Sections 8.7 and 9.1). With walls set to aerodynamically straight contours the slopes are high and conversely with walls set to constant pressure contours, with the magnitude of the errors increasing with Mach number. The opposite sign of the interference is of course an example of the phenomenon which led to the suggestion of ventilation as a means for reducing wall interference.

A further illustration of the existence of interferences with the walls set to constant pressure contours is shown in Table 6. None of the contours satisfy the normal wall streamlining criteria ($E < 0.01$ on both walls) and therefore the resulting interference effects are larger than usually experienced when the walls are streamlined (see Section 2.2 for typical values of residual interference effects when the walls are streamlined). Typical effects on model pressure distributions of moving the walls from straight to constant pressure contours are illustrated on Figures 10.1-10.3. In each case over-correction is clear.

8.5 Effects of Moving from Straight* to Streamlined Walls

The strong interference induced by straight walls is well illustrated on Figures 15.1 and 15.2, lift-incidence curves for reference Mach numbers of 0.4, 0.5 and 0.6. Straight wall lift curve slopes are seen to be much greater than the corresponding streamlined wall slopes, the latter group being in rough agreement with each other. The lift curve slopes are summarised in Table 5. There is further information on straight wall interference in Table 7, which contains wall loadings (measured in terms of E) associated with straight walls and with walls streamlined according to the NPL strategies. The values of E are seen to be much reduced by both of the NPL strategies, but neither strategy is consistently as good as the TSP and WAS 1 strategies which, as noted in Section 2.2, generally bring E below 0.01 on both walls.

The effects on model pressure distributions of streamlining the walls according to the NPL strategies are presented on Figures 10.1-10.3. The strength of interference which

* The word "*straight*" refers to aerodynamically straight (not geometrically straight).

is possible with straight walls is best illustrated on Figure 10.3 ($M_\infty = 0.7$; $\alpha \approx 4.0^\circ$). For this test condition there is a strong shock on the model's upper surface at about 55% chord when the walls are set straight. After streamlining alone (with no other change) the recompression shock is positioned at about 25% chord. This is associated with a reduction in the value of boundary layer pressure drag (form drag) coefficient which is another typical effect of streamlining at high Mach numbers. These effects of streamlining (by now very familiar to those working with transonic flexible walled test sections) are also illustrated in the corresponding schlieren pictures on Figure 11, where in the lower picture the walls have been streamlined according to the WAS 1 strategy but with essentially the same effect on the model behaviour as the NPL strategies (as confirmed on Figure 14.14).

The Mach number distributions along walls set to aerodynamically straight and streamlined contours are shown on Figures 12.1-12.5. The figures show the Mach number at the centrelines of both walls derived from a measurement of static pressure at each of the jack positions. The strong interference induced by straight walls modifies the wall Mach number distribution around the model and can cause the model's shocks to be misplaced and modified in strength (as already has been shown), or can cause shocks to occur where they should not. In some severe cases this can lead to complete choking of the straight walled test section, although in the cases presented here such conditions were not quite reached. However, in some cases the channel over the upper surface of the model was choked with straight walls as illustrated on Figure 12.5 ($M_\infty = 0.7$; $\alpha \approx 4.0^\circ$). In this example the shock on the upper surface of the model had reached the top wall giving a maximum wall Mach number of approximately 1.05. Streamlining the walls (according to several strategies) reduced the maximum top wall Mach number to around 0.8 for this test condition.

Another effect of streamlining is in the wall Mach numbers existing in the region downstream of the model. As has been seen from the earliest days¹, during the streamlining process the walls automatically adapt to the blockage caused by the model's wake. In the case of straight walls the wall Mach number downstream of the model asymptotes to a value well above the reference value, as is seen on Figures 12.1-12.5. This phenomenon was one which in 1937 led NPL to the use of liners⁵ and then adaptive flexible walls in transonic testing.^{5,7-10,12} When the walls are streamlined the wall Mach number downstream of the model is seen to return essentially to the reference value, as must be the case in simulating free flowfield conditions.

8.6 Streamlined Wall Contours

Streamlined wall contours adopted by the various wall adjustment strategies for the 0.4 to 0.7 Mach sweep at an angle of incidence of 4.0° are shown on Figures 13.1.1-13.4.2. An effect of compressibility is visible in the walls moving apart in the region of the model, progressively more rapidly as the Mach number is increased. Also noticeable is the movement apart of the flexible walls downstream of the model to eliminate wake blockage, as illustrated on Figures 13.1.2, 13.2.2, 13.3.2 and 13.4.2. It is important to note that contours derived by the NPL strategies only partially alleviate wake blockage, but this point is discussed further in Section 9.3. It should be re-emphasised that the walls take up these streamlined contours quite automatically, in response to measurements made only at the flexible walls.

Despite the fact that the flexible walls are relatively long, extending to about 5 chords upstream and downstream of the model, in some test cases the streamlined wall contours have noticeable slopes at the ends of the test section. This is an indication of the circulation-induced disturbance which led to the requirement of mounting the model symmetrically in the streamlined portion of the test section (as discussed in Section 5.2 and Reference 16).

The streamlined wall contours adopted by the TSP and WAS 1 strategies have different displacement characteristics. In general, contours derived by the TSP strategy exhibit wall displacements of greater magnitude than those derived by the WAS 1 strategy, as illustrated on Figures 13.1.1, 13.2.1, 13.3.1 and 13.4.1. When the model is generating lift the wall displacements are typically positive for the top wall and negative for the bottom wall, where displacements away from the test section centreline (usually with respect to aerodynamically straight contours) are considered positive. The disparities between the contours may give the impression that the different walls must give different flow characteristics at the model. However from the earliest days¹, it has been evident that it is possible for a wall to attach itself to, and then follow, any streamline passing over or under the model and not disturb the model. Hence different wall contours can represent different but equally valid streamlines for a given test condition. The flexible walls are anchored at a fixed point upstream of the model, which suggests that a wall can only take one shape to be streamlined as only one streamline passes through the anchor point. However, in practice, when streamlined the wall follows the shape of a streamline that has been '*picked-up*' by the wall not at the fixed anchor point but rather at the first jack position, which is of course moveable. The shape of the

streamline which is picked-up depends on the displacement of the first jack and therefore wall contours of different shape, within limits, may be termed streamlined for a given test condition. Analysis of model performance (see Section 8.7 and Figures 14.1-14.14) demonstrates that such contours result in the same flow conditions around the model, despite the variations in wall loading just downstream of the anchor point between one streamlined wall contour and another.

When streamlined wall contours derived by the TSP and WAS 1 strategies are analysed in terms of total wall movement (that is wall movement apart), then good agreement between the two strategies is found, as illustrated on Figures 13.1.2, 13.2.2, 13.3.2 and 13.4.2. Both strategies move the walls outward downstream of the model by roughly the same amount, but to a greater extent than by the NPL strategies. Therefore it may be concluded that the NPL strategies do not fully account for the model wake (Section 9.3 discusses this point in greater detail). Further inspection of the Figures (13.1.2, 13.2.2, 13.3.2 and 13.4.2) reveals that the NPL strategies select contours which exhibit less total wall movement than the TSP and WAS 1 strategies. The NPL strategy employing a setting factor of six-tenths (NPL 2 WAS) appears, on the evidence of wall contours, to be more appropriate than the strategy employing a half-way setting factor (NPL 1 WAS).

8.7 Model Data

Model pressure distributions were measured and recorded at every stage of the test programme, but are reproduced (aside from the selected cases already discussed) only for cases where the walls were streamlined according to the various strategies. The pressure distributions and the force and moment coefficients derived from the pressures are shown on Figures 14.1-14.14 for each test condition. Figures 15.1-15.5 summarise force coefficient data for straight*, constant pressure and streamlined walls. The lift curve slopes for reference Mach numbers of 0.4, 0.5 and 0.6 are summarised in Table 5 and the variation of normal force coefficient with Mach number for all the data sets ($\alpha = 0.5^\circ$, 2.0° and 4.0°) are shown on Figure 16.

Inspection of Figures 14.1-14.14 shows that the model pressure distributions obtained when the walls were streamlined by the TSP and WAS 1 strategies are in excellent agreement, as expected. The lift curve slopes show good agreement (see Table 5

* Where it was possible to run with walls set to aerodynamically straight contours.

and Figures 15.1-15.3), whilst the model's upper surface shock position for test conditions $M_\infty = 0.8$; $\alpha \approx 2.0^\circ$ and $M_\infty = 0.7$; $\alpha \approx 4.0^\circ$ agree to within about 3% and 1% of chord respectively, as illustrated on Figures 14.10 and 14.14. With pressure orifices positioned only at each 5% chord it is difficult to be more precise.

Model data obtained when the walls were streamlined according to the NPL strategies generally compares very well with that obtained employing the TSP and WAS 1 strategies, especially for reference Mach numbers up to 0.7. For example, at the relatively severe test condition of $M_\infty = 0.7$; $\alpha \approx 4.0^\circ$ there is excellent agreement between the four strategies in the position of the model's upper surface shock, as shown on Figure 14.14. However, in general, comparison of model pressure distributions reveals that the velocity of the flow around the model was slightly greater when the walls were streamlined according to the NPL strategies as opposed to the TSP and WAS 1 strategies. As this was true to about the same extent (in terms of C_p) for the upper and lower surfaces of the model, the derived force coefficients (and hence lift curve slopes) show good agreement. The force coefficient data is summarised in Table 5 and on Figures 15.1-15.5 and 16. Hence on the evidence of model data, wall streamlining according to both NPL strategies appears to result in near interference-free test conditions for speeds up to about Mach 0.7 for the present model in the particular test section configuration of the TSWT.

At some test conditions both of the NPL strategies completely break down. This is apparent in the model pressure distributions shown on Figures 14.5 ($M_\infty = 0.8$; $\alpha \approx 0.5^\circ$) and 14.10 ($M_\infty = 0.8$; $\alpha \approx 2.0^\circ$). In these cases the model shocks are stronger and misplaced with the NPL strategies, compared to those obtained when streamlining according to the TSP and WAS 1 strategies, eventually leading to choking of the test section. Schlieren pictures of a representative case are shown on Figure 17, the pictures clearly demonstrate the effects of the breakdown of the NPL strategy (NPL 2 WAS). A consequence of the breakdown is reduced model lift, as illustrated by the relatively low C_N values obtained when using the NPL strategy at the test conditions of $M_\infty = 0.8$; $\alpha \approx 0.5^\circ$ and $M_\infty = 0.8$ and $\alpha \approx 2.0^\circ$, as shown on Figure 16.

In tests in the NPL Tunnel which used a model with an EC 1250 section of 5 inch chord, breakdown of their strategy (NPL 1 WAS) had not yet become evident at test conditions of $M_\infty = 0.886$; $\alpha = 0.0^\circ$ and $M_\infty = 0.827$; $\alpha = 4.0^\circ$. That is to say at such conditions the model shocks had not reached the contoured walls. The relatively early breakdown of the strategy in the TSWT is evidence that the present evaluation is a more severe test of the effectiveness of the NPL strategy than the original NPL investigations.

The scope of the present investigation does not allow the boundary of the test regime within which the NPL strategy performs satisfactorily in the TSWT to be accurately defined.

9. FURTHER NOTES ON THE NPL STRATEGY

9.1 Streamlining Quality of NPL Contours

Wall streamlining quality is determined from wall loadings arising from the differences between the test section and imaginary flowfields; parameter E has been introduced as a measure of wall loading. In order to assess the streamlining quality of contours derived by the NPL strategies wall loading values were calculated at each test condition, with the TSWT TSP code being used in the computations of the imaginary flowfields. The residual interference effects at the model due to any remaining wall loading were also calculated using linearised theory.²

The results, presented in Tables 7 and 8, clearly illustrate that employment of the NPL strategy considerably reduces the level of wall loading from that present with straight walls. It is evident that a setting factor of six-tenths (NPL 2 WAS) is more appropriate than the half-way factor (NPL 1 WAS). Contours derived by the former setting factor nearly satisfy the normal streamlining criteria ($E < 0.01$ on both walls) for speeds up to about Mach 0.7. However, analysis of model performance suggests that the streamlining criteria may well be unnecessarily strict, especially up to Mach 0.7. Also noticeable from the results presented in Tables 7 and 8 is that wall loading and hence residual interferences increase with angle of incidence. Therefore the lift generated by the model may be a factor limiting the test regime where the NPL strategy can be considered applicable. Finally, the breakdown of the NPL strategy above Mach 0.7 is clearly demonstrated by excessive wall loading remaining after wall streamlining, as shown in Table 7.

9.2 Convergence of Walls to NPL Contours

A prerequisite of setting wall contours according to the NPL strategy is the determination of constant pressure contours and therefore the rate of wall convergence to the latter contours determines the number of wall adjustments necessary during the NPL streamlining process. When employing the Imbalance strategy* satisfactory constant pressure contours were reached only after many iterations. However, utilising the WAS 1 strategy but with the perturbations of the imaginary flowfields all the while artificially set to zero improved the situation, although convergence was still slow. Generally, wall streamlining according to the NPL strategy required 3 to 5 times as many streamlining

* See Section 6 for details of the Imbalance strategy.

iterations than the TSP and WAS 1 strategies. This represents the only major operational disadvantage associated with the implementation of the NPL strategy. The TSP and WAS 1 strategies have been developed to rapidly derive streamlined wall contours. Presumably a predictive strategy could be developed to derive constant pressure contours, but at present there does not appear to be any immediate need for this development.

9.3 Model Wake Approximation

As has been previously noted, properly streamlined walls automatically adapt to the blockage caused by the model wake. The wall Mach number some distance downstream of the model returns essentially to the reference value, as must be the case for the simulation of free flowfield conditions.

By definition, constant pressure walls with a model present, and aerodynamically straight walls with no model both exhibit constant Mach number, equal to the reference value, along the centrelines of the flexible walls. For constant pressure contours this requires outward wall movement (relative to aerodynamically straight) downstream of the model in order to eliminate the blockage caused by the model wake. The NPL strategy requires wall contours of reduced outward movement downstream of the model than the contours giving constant pressure, thus raising the wall Mach number in this region above the reference value. Therefore the NPL strategy cannot totally eliminate model wake blockage. McKinnon Wood³⁴ noted this limitation in 1944. The problem is exaggerated at speeds where the effect of setting the walls to streamlined contours from constant pressure contours is to increase the strength of model shocks because of the almost inevitable increase in the thickness of the wake, as shown on Figure 10.3.

In practice, however, for speeds up to Mach 0.7 the inadequate alleviation of wake blockage, caused by the approximate nature of the NPL strategy, appears to be of little consequence. The evidence is provided by model data (as discussed in Section 8.7) and the measurement of wall Mach numbers downstream of the model which show them to be close to the reference value, as shown on Figures 12.1-12.5. At Mach 0.8 where breakdown of the NPL strategy is evident, the downstream wall Mach numbers are appreciably higher than the reference value, as shown on Figure 18. At this speed the wake blockage approximation becomes more significant as the shock induced separation of the model boundary layer has led to increased wake thickness, as can be detected from the schlieren pictures shown on Figure 17.

In order to try to indicate the magnitudes of the effects on model performance of the inadequate alleviation of wake blockage, a 'wake pinch' test was performed in the TSWT. For the test condition of $M_\infty = 0.8$; $\alpha \approx 6.0^\circ$ model data obtained with walls streamlined according to the WAS 1 strategy was compared to that obtained with the walls set to a contour moved deliberately to cause wake blockage. The displacements (relative to aerodynamically straight) of both wall contours are shown on Figure 19.1. The large outward displacement downstream of the model exhibited by the properly streamlined contour (WAS 1) indicates a model wake of considerable thickness (from jack 17 to 20 the displacement thickness is about 0.15 inches). The high downstream wall Mach numbers exhibited by the other contour (CONTOUR 1) shown on Figure 19.2 suggests significant wake blockage. The downstream Mach number on the top and bottom walls is seen to have risen from 0.8 to about 0.85. The expected effect of such blockage on the model was to increase the flow velocity near the trailing edge. However, comparison of the corresponding model pressure distributions (see Figure 19.3) reveals that no effect on model performance was detectable. Therefore, it may be tentatively concluded that the effects of the NPL wake approximation was insignificant for most test conditions of the present investigation.

9.4 Appropriate NPL Setting Factor for the TSWT

Analysis of streamlined wall contours has suggested that for the model and test section configuration of the present investigation a setting factor of seven-tenths towards the constant pressure contour would be more appropriate than the two setting factors suggested by NPL. An NPL strategy employing a factor of seven-tenths (NPL 3 WAS) derives wall contours that exhibit approximately the same wall movement apart characteristics in the vicinity of the model as the TSP and WAS 1 strategies. However, it should be emphasised that disparities between the strategies, in terms of wall movement apart, still exist upstream and downstream of the model, as illustrated by the representative case ($M_\infty = 0.7$; $\alpha \approx 4.0^\circ$) shown on Figure 13.4.2. Model tests with the flexible walls adjusted according to the new setting factor are required in order to assess the streamlining performance of the strategy (NPL 3 WAS). However, it is anticipated that employment of a seven-tenths setting factor would delay the breakdown of the NPL strategy in the TSWT.

10. PRINCIPAL CONCLUSIONS

- 1) The wall adjustment strategy proposed and developed by NPL in the 1940s for use in their transonic self-streamlining flexible walled wind tunnel, has been extensively evaluated in the TSWT by streamlining around a two-dimensional aerofoil model giving a ratio of test section height to chord of 1.5. This is a more severe streamlining environment than that for which NPL developed the strategy.
- 2) An assessment of streamlining quality indicates that with the walls streamlined according to the NPL strategy the top and bottom wall interferences are significantly reduced from the levels present with straight walls.
- 3) Comparison of model data obtained with walls streamlined according to several modern strategies suggests that the NPL strategies, in particular that which employs a setting factor of six-tenths, reduce top and bottom wall interference to a level which may be considered insignificant for test conditions up to $M_\infty = 0.7$; $\alpha \approx 4^\circ$.
- 4) The test regime within which the NPL strategy performs satisfactorily appears to be limited. The strategy has been observed to break down at a reference Mach number of 0.8. Higher values of model lift may well further restrict the applicable Mach number.
- 5) For the test section and model configuration of the present investigation an NPL strategy employing a setting factor of seven-tenths appears to be more appropriate than the setting factors suggested by NPL.
- 6) The only significant disadvantage associated with the NPL strategy, within the applicable test regime, when compared with more complex and modern strategies was the number of wall adjustments necessary during the streamlining process. This disadvantage may be reduced by further effort applied to improving the technique.
- 7) The only major development in the flexible walled testing technique since the 1940's, apart from the reduction of tunnel run-time attributable to the streamlining process, is the reduction of the ratio of test section height to model chord from about 3.5 to about 1.5.

11. LIST OF SYMBOLS

α	Angle of incidence
A_1	Lift curve slope per Radian
C or c	Model chord
C_D or C_D	Boundary layer pressure drag coefficient (Form drag coefficient)
C_L or C_L	Lift coefficient
C_M	Pitching moment coefficient about the leading edge
C_N	Normal force coefficient
C_P or C_p	Pressure coefficient
C_P^*	Sonic pressure coefficient
δ^*	Boundary layer displacement thickness
E	Average of the modulus of the set of pressure difference coefficients determined at each jack along a wall
E_T	Value of E for the top wall
E_B	Value of E for the bottom wall
E^*	Value of E when the perturbations of the imaginary flowfields are artificially set to zero
M	Mach number
M_∞	Reference Mach number
σ_{av}	Average weighted standard deviation of a pair of walls
σ	Standard deviation of wall centreline Mach number errors
σ_T	Value of σ for the top wall
σ_B	Value of σ for the bottom wall
X	Chordwise position from the leading edge
Y	Model surface displacement from the leading edge

12. REFERENCES

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TABLE 1:- CO-ORDINATES OF THE NACA 0012-64 SECTION

Section Co-ordinates	
X/c	Y/c
0.0	0.0
0.005	0.0118
0.01	0.0163
0.015	0.0196
0.02	0.0223
0.025	0.0245
0.035	0.0283
0.05	0.0327
0.07	0.0372
0.085	0.04
0.1	0.0424
0.14	0.0475
0.17	0.0505
0.2	0.0529
0.25	0.0561
0.3	0.0583
0.35	0.0596
0.4	0.06
0.45	0.0596
0.5	0.0583
0.55	0.0561
0.6	0.0531
0.65	0.0494
0.7	0.0448
0.75	0.0394
0.8	0.0332
0.85	0.0263
0.9	0.0187
0.95	0.0103
1.0	0.0012

TABLE 2: PRESSURE PORT CO-ORDINATES OF THE NACA 0012-64 SECTION

Pressure Port Co-ordinates			
X/c	$Y_{upper/c}$	X/c	$Y_{lower/c}$
0.011	0.0177	0.011	0.0182
0.024	0.0235	0.025	0.024
0.048	0.0321	0.05	0.0326
0.077	0.0381	0.074	0.0375
0.098	0.0418	0.098	0.0418
0.152	0.0491	0.151	0.049
0.2	0.0534	0.2	0.0535
0.251	0.0563	0.25	0.0562
0.299	0.0579	0.299	0.0579
0.35	0.0595	0.35	0.0595
0.398	0.06	0.402	0.06
0.448	0.0596	0.449	0.0595
0.499	0.0583	0.5	0.0582
0.549	0.0562	0.552	0.0561
0.599	0.0532	0.601	0.0531
0.649	0.0494	0.649	0.0495
0.698	0.0449	0.702	0.0445
0.749	0.0395	0.751	0.0393
0.799	0.0334	0.801	0.0311
0.848	0.0266	0.85	0.0263
0.902	0.0184	0.9	0.0187
0.949	0.0105	0.95	0.0102

Reference Mach Number (M_∞)	Contour	Designated Mach Number Band	Standard Deviation of Local Mach Number (Wall Centreline)		Average Weighted Standard Deviation (σ_{av})
			Top Wall (σ_T)	Bottom Wall (σ_B)	
0.4	A	up to 0.45	0.0014	0.0015	0.0036
0.5	B	0.45-0.55	0.0012	0.0020	0.0032
0.6	C	0.55-0.65	0.0014	0.0024	0.0032
0.7	D	0.65-0.75	0.0023	0.0029	0.0037
0.8	E	above 0.75	0.0029	0.0031	0.0037

TABLE 3: QUALITY OF AERODYNAMICALLY STRAIGHT WALL CONTOURS

Reference Mach Number (M_∞)	Contour	Model Incidence (Deg)	Standard Deviation of Local Mach Number (Wall Centreline)		Average Weighted Standard Deviation (σ_{av})	Artificial Wall Loading	
			Top Wall (σ_T)	Bottom Wall (σ_B)		$E_T^{*(1)}$	$E_B^{*(1)}$
0.4	A.1	0.5	0.0021	0.0022	0.0054	0.0070	0.0066
	A.2	2.0	0.0016	0.0015	0.0041	0.0061	0.0042
	A.3	4.0	0.0032	0.0032	0.0080	0.0148	0.0120
0.5	B.1	0.5	0.0019	0.0024	0.0043	0.0049	0.0056
	B.2	2.0	0.0018	0.0013	0.0031	0.0053	0.0036
	B.3	4.0	0.0034	0.0040	0.0074	0.0124	0.0096
0.6	C.1	0.5	0.0021	0.0025	0.0038	0.0043	0.0043
	C.2	2.0	0.0029	0.0021	0.0042	0.0050	0.0042
	C.3	4.0	0.0040	0.0040	0.0067	0.0097	0.0089
0.7	D.1	0.5	0.0020	0.0021	0.0029	0.0029	0.0030
	D.2	2.0	0.0028	0.0020	0.0034	0.0031	0.0028
	D.3	4.0	0.0046	0.0052	0.0070	0.0074	0.0086
0.8	E.1	0.5	0.0028	0.0020	0.0030	0.0040	0.0022
	E.2	2.0	0.0035	0.0034	0.0043	0.0034	0.0035

TABLE 4: QUALITY OF CONSTANT PRESSURE WALL CONTOURS

Note:- (1) When determining values for E^* the perturbations of the imaginary flowfields were artificially set to zero.

Wall Adjustment Strategy (Walls Streamlined)	Approx. Lift Curve Slope per Radian (A1)		
	Mach 0.4	Mach 0.5	Mach 0.6
WAS 1	5.02	5.22	5.61
TSP WAS	4.95	5.17	5.53
NPL 1 WAS	5.04	5.33	5.33
NPL 2 WAS	5.01	5.19	5.29
Walls Set Straight	5.96 (+ 19%)	6.49 (+ 24%)	8.22 (+ 47%)
Walls Set to Constant Pressure	4.39 (-12%)	4.47 (-14%)	4.42 (-20%)

TABLE 5: SUMMARY OF LIFT CURVE SLOPES

Note: Values in brackets are the % changes of lift curve slope when compared with the WAS 1 slope.

Test Condition		Quality of Wall Streamlining		Interference Effects		
Model Incidence (Deg)	Reference Mach Number (M_{ref})	E_T	E_B	α Error (Deg)	Camber Error (Deg)	C_p Error
0.5	0.4	0.0104	0.0088	0.0070	0.0388	0.0094
	0.5	0.0158	0.0144	0.0071	0.0335	0.0144
	0.6	0.0197	0.0181	0.0035	0.0389	0.0153
	0.7	0.0251	0.0230	0.0045	0.0393	0.0205
	0.8	0.0354	0.0314	0.0278	0.0742	0.0262
2.0	0.4	0.0246	0.0079	0.0605	0.3250	0.0148
	0.5	0.0310	0.0120	0.0510	0.3642	0.0165
	0.6	0.0299	0.0122	0.0555	0.3704	0.0157
	0.7	0.0375	0.0169	0.0613	0.4012	0.0181
	0.8	0.0470	0.0216	0.1045	0.530	0.0244
4.0	0.4	0.0494	0.0138	0.1251	0.6842	0.0158
	0.5	0.0493	0.0165	0.1397	0.7692	0.0162
	0.6	0.0603	0.0214	0.1361	0.8609	0.0190
	0.7	0.0640	0.0249	0.1498	0.9289	0.0209

TABLE 6: STREAMLINING QUALITY AND INTERFERENCE EFFECTS OF CONSTANT PRESSURE WALL CONTOURS

Note: The interference effects at the model due to the existence of wall loading, measured in terms of E , was determined from the TSWT TSP pressure measurements.

*ed using linearised theory. The wall
^a imaginary flowfields) and wall

Test Condition		Quality of Wall Streamlining					
Model Incidence (Deg)	Reference Mach Number (M_∞)	Aerodynamically Straight Contours		NPL 1 WAS Contours		NPL 2 WAS Contours	
		E_T (1)	E_B (1)	E_T (2)	E_B (2)	E_T (2)	E_B (2)
0.5	0.4	0.0342	0.0368	0.0133	0.0161	0.0101	0.0126
	0.5	0.0372	0.0371	0.0135	0.0151	0.0094	0.0126
	0.6	0.0437	0.0430	0.0139	0.0160	0.0111	0.0120
	0.7	0.0437	0.0515	0.0158	0.0178	0.0111	0.0125
	0.8			0.0808	0.0853	0.0237	0.0270
2.0	0.4	0.0509	0.0273	0.0176	0.0147	0.0083	0.0098
	0.5	0.0522	0.0282	0.0155	0.0152	0.0073	0.0114
	0.6	0.0569	0.0320	0.0173	0.0151	0.0095	0.0118
	0.7	0.0737	0.0419	0.0194	0.0186	0.0093	0.0153
	0.8			0.0583	0.0733	0.0464	0.0645
4.0	0.4	0.0760	0.1710	0.0209	0.0072	0.0142	0.0063
	0.5	0.0768	0.0237	0.0213	0.0099	0.0113	0.0131
	0.6	0.0856	0.0264	0.0192	0.0123	0.0135	0.0128
	0.7	0.1251	0.0676	0.0264	0.0185	0.0133	0.0178

TABLE 7: STREAMLINING QUALITY OF WALL CONTOURS DERIVED BY THE NPL STRATEGY

Note: (1) For aerodynamically straight contours the perturbations in the imaginary flowfields are zero.

(2) When determining values for E (NPL contours only) the TSWT TSP code was used to predict the imaginary flowfields.

Test Conditions		Residual Interference Effects						
Model Incidence (Deg)	Reference Mach Number (M_∞)	NPL 1 WAS Contours				NPL 2 WAS Contours		
		α Error (Deg)	Camber Error (Deg)	C_p Error		α Error (Deg)	Camber Error (Deg)	C_p Error
0.5	0.4	0.0200	0.0088	-0.0160		0.0109	0.0269	-0.0127
	0.5	0.0041	-0.0063	-0.0159		0.0108	0.0166	-0.0119
	0.6	0.0078	0.0080	-0.0182		0.0032	0.0106	-0.0121
	0.7	0.0100	0.0044	-0.0192		0.0044	0.0151	-0.0124
	0.8	0.0328	0.0659	-0.0962		0.0218	0.0411	-0.0288
2.0	0.4	-0.0044	-0.0091	-0.0180		0.0079	0.0598	-0.0091
	0.5	0.0008	0.0131	-0.0171		0.0058	0.0690	-0.0099
	0.6	-0.0016	-0.0029	-0.0193		0.0055	0.0701	-0.0117
	0.7	-0.0054	0.0026	-0.0233		0.0068	0.1031	-0.0134
	0.8	0.0626	0.2106	-0.0771		0.0871	0.3088	-0.0623
4.0	0.4	-0.0244	-0.0780	-0.0115		0.0063	0.0811	-0.0076
	0.5	-0.0252	-0.0452	-0.0165		0.0134	0.1274	-0.0111
	0.6	-0.0161	0.0069	-0.0161		0.0287	0.1924	-0.0080
	0.7	-0.0281	-0.0569	-0.0247		0.0199	0.1651	-0.0149

TABLE 8: RESIDUAL INTERFERENCE EFFECTS OF WALL CONTOURS DERIVED BY THE NPL STRATEGY

Note: The residual interference effects at the model due to the existence of wall loading are calculated using linearised theory. The wall loading, measured in terms of E , was determined from the TSWT TSP code (to predict the imaginary flowfields) and wall pressure measurements.

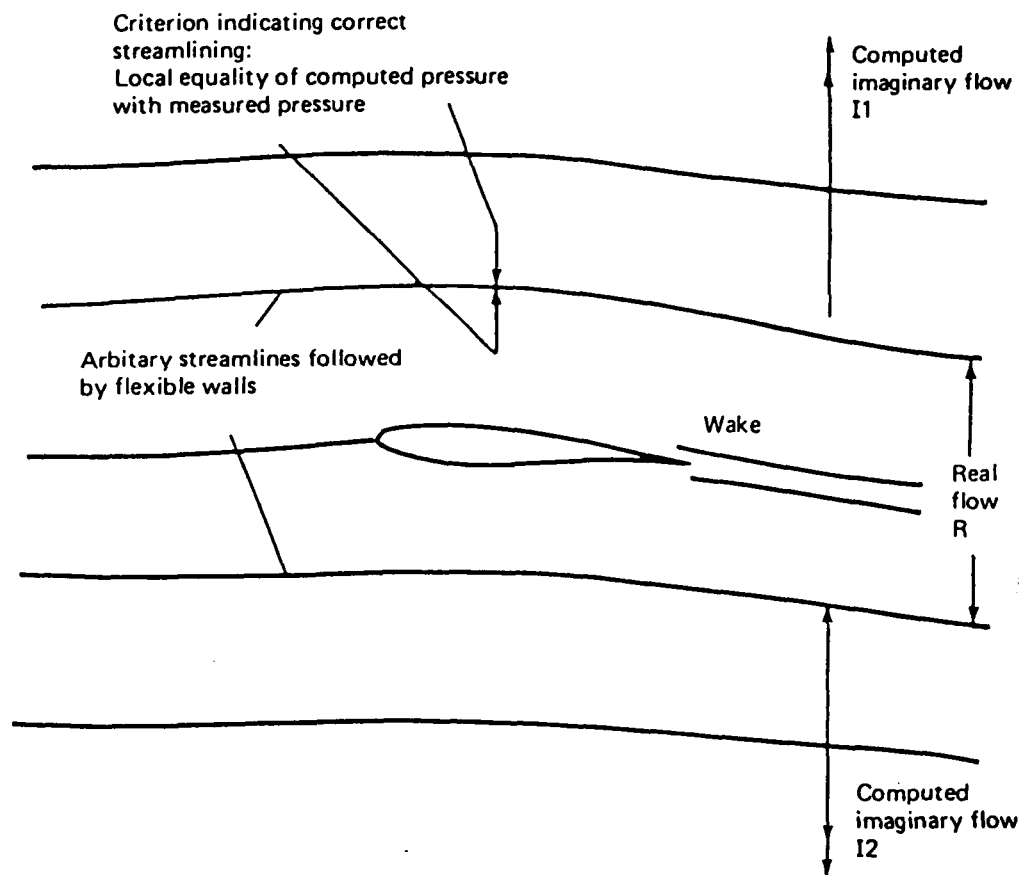
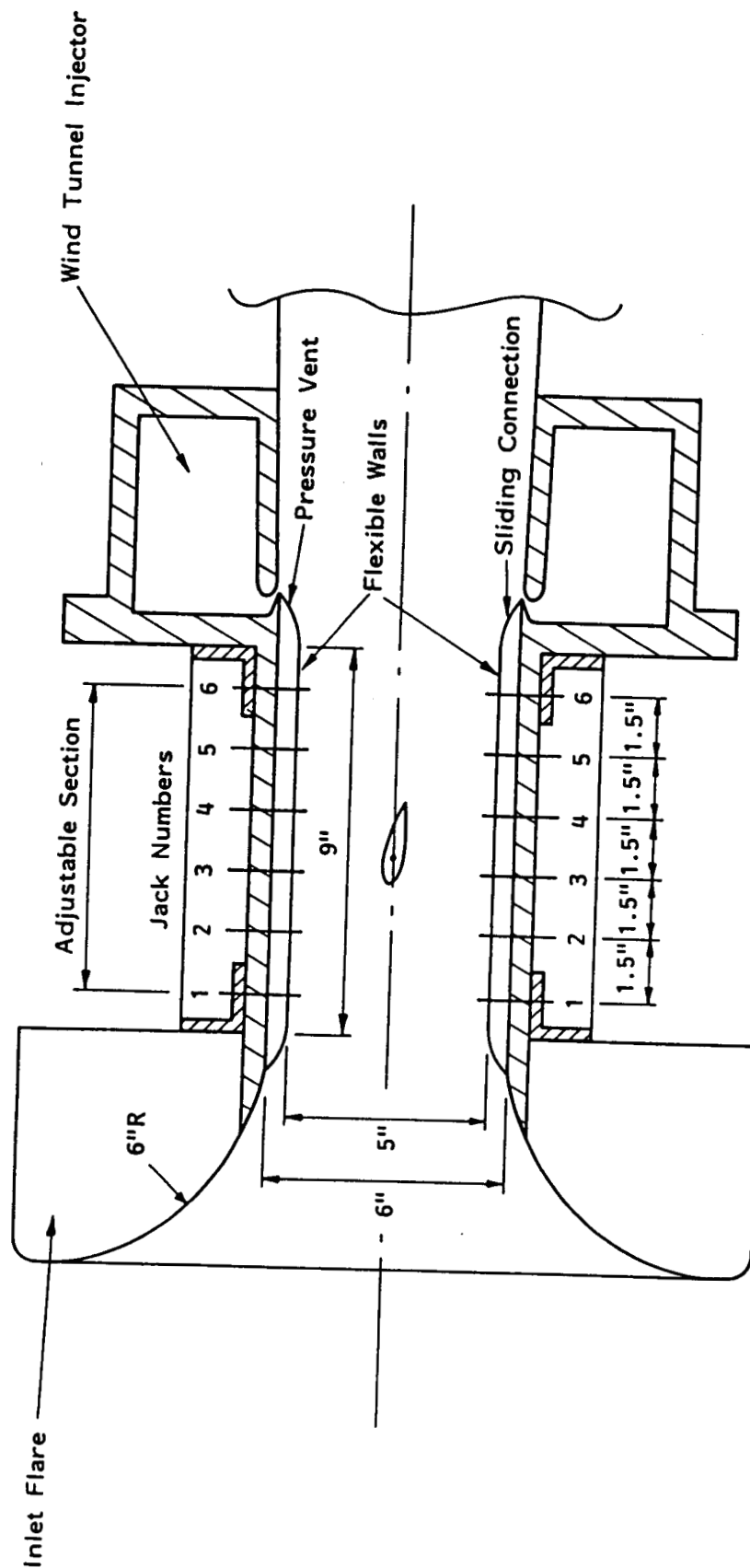
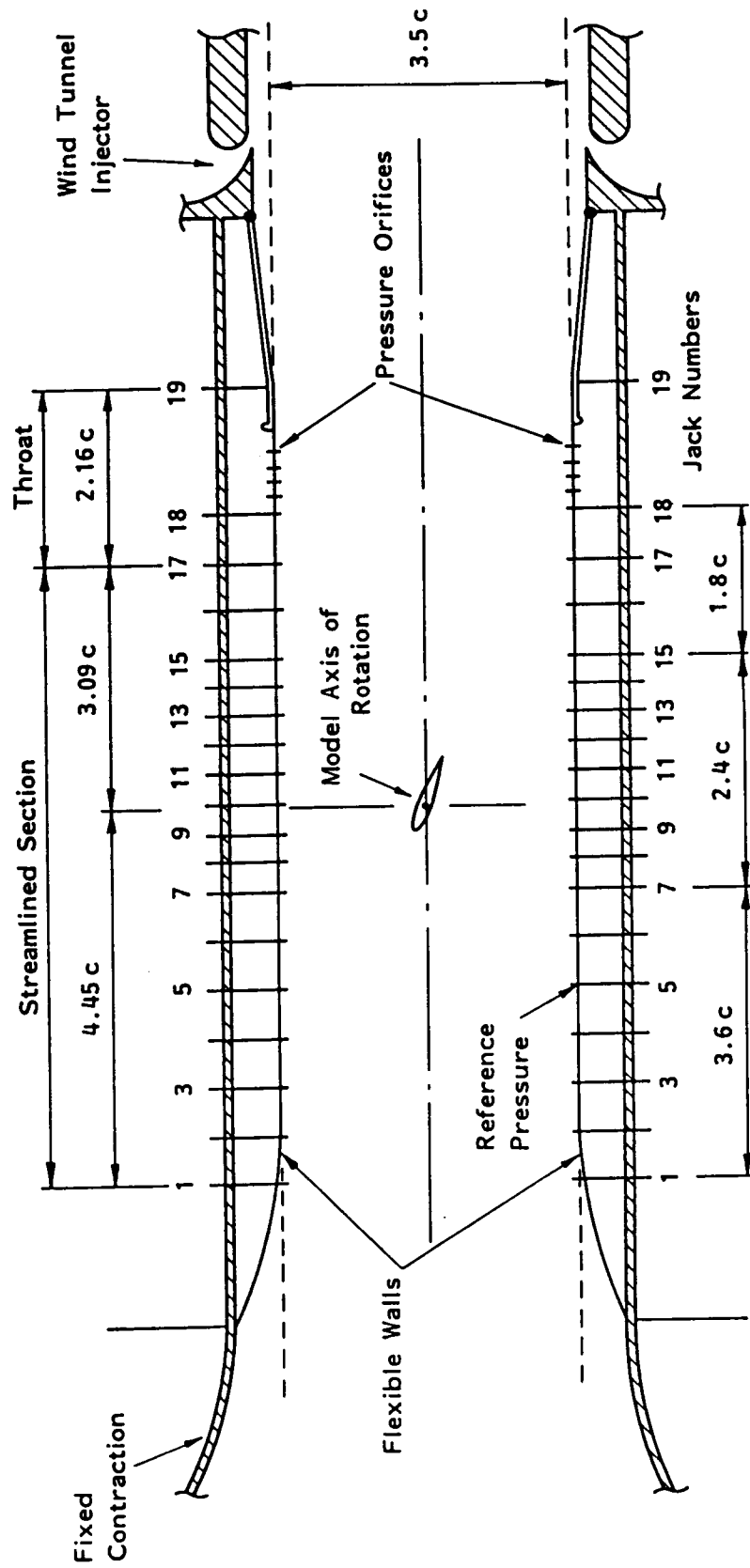


FIG. 1 A TWO-DIMENSIONAL FLOWFIELD ILLUSTRATING THE PRINCIPLE OF TEST SECTION STREAMLINING



Scale 1:4 approx.

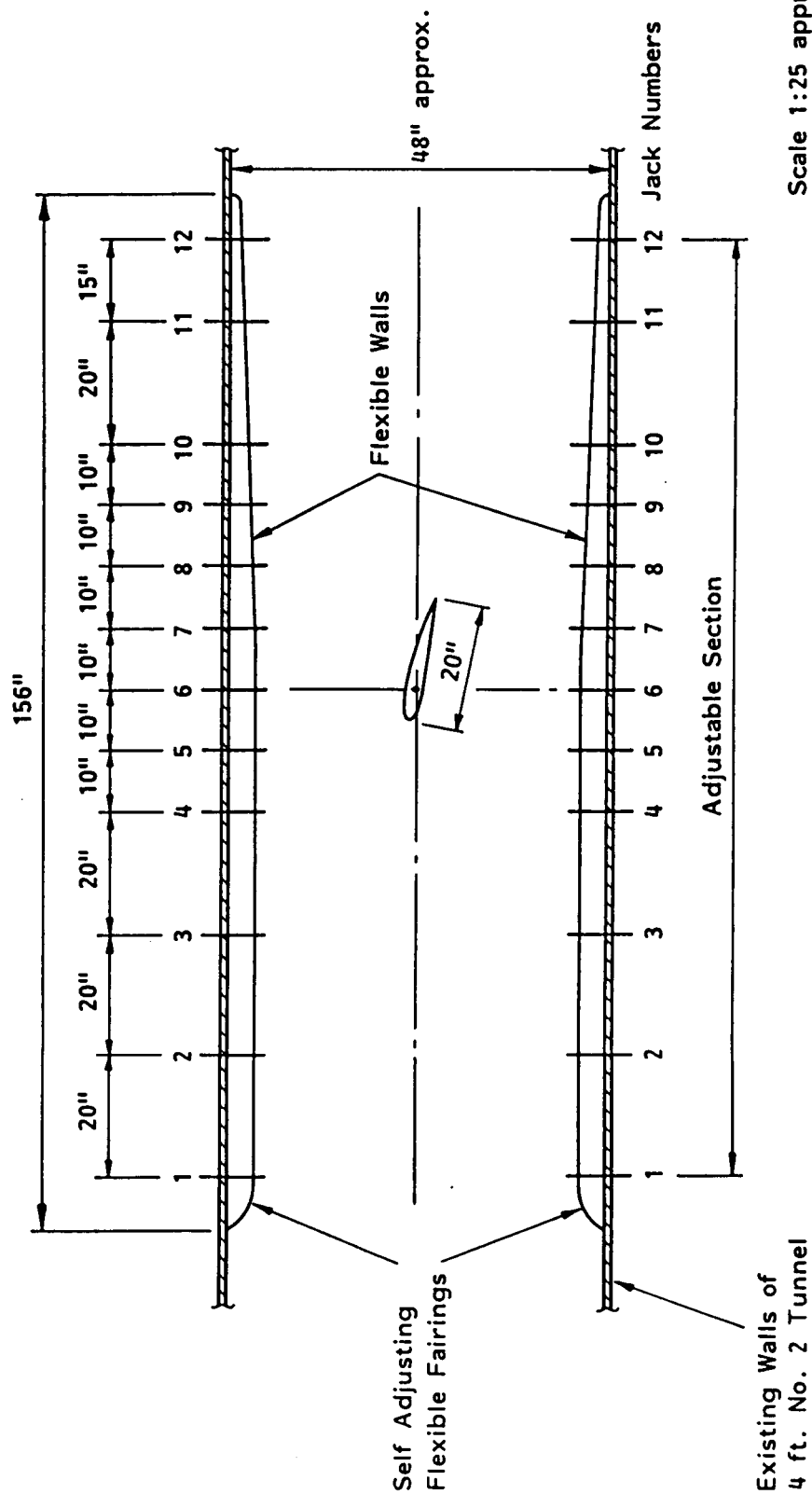
FIG. 2 SCHEMATIC LAYOUT OF NPL 5 inch x 2 inch TRANSONIC ADAPTIVE WALL WIND TUNNEL (1938)



c = Aerofoil chord (= 5.0 inches)

Scale 1:10 approx.

FIG. 3 SCHEMATIC LAYOUT OF NPL 20 inch x 8 inch RECTANGULAR TRANSONIC WIND TUNNEL (1941)



Scale 1:25 approx.

FIG. 4 SCHEMATIC LAYOUT OF NPL 4 ft. NO. 2 TUNNEL FITTED WITH FLEXIBLE WALLS (1944)

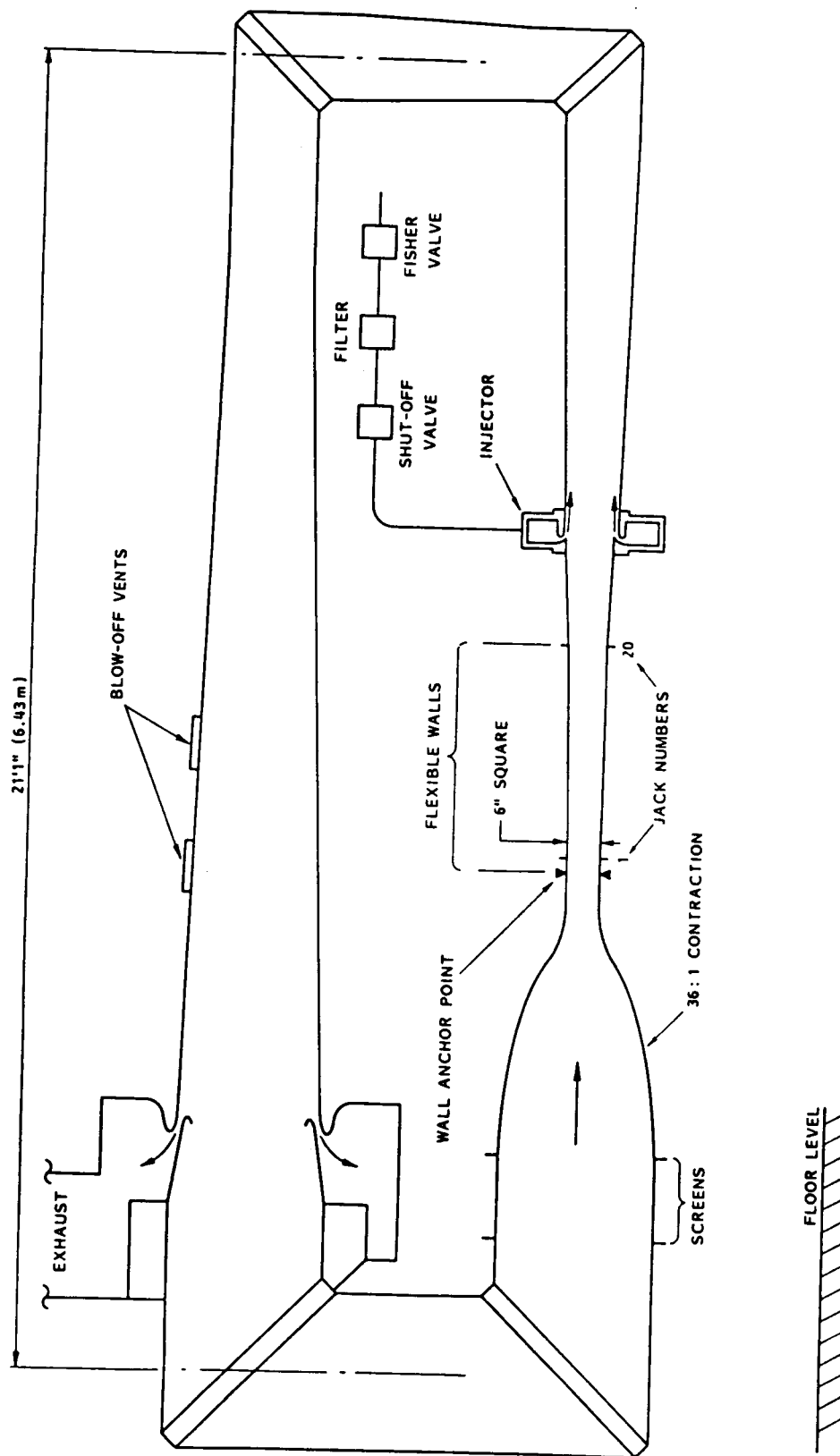


FIG. 5 AERODYNAMIC LINES OF THE TRANSONIC SELF-STREAMLINING WIND TUNNEL

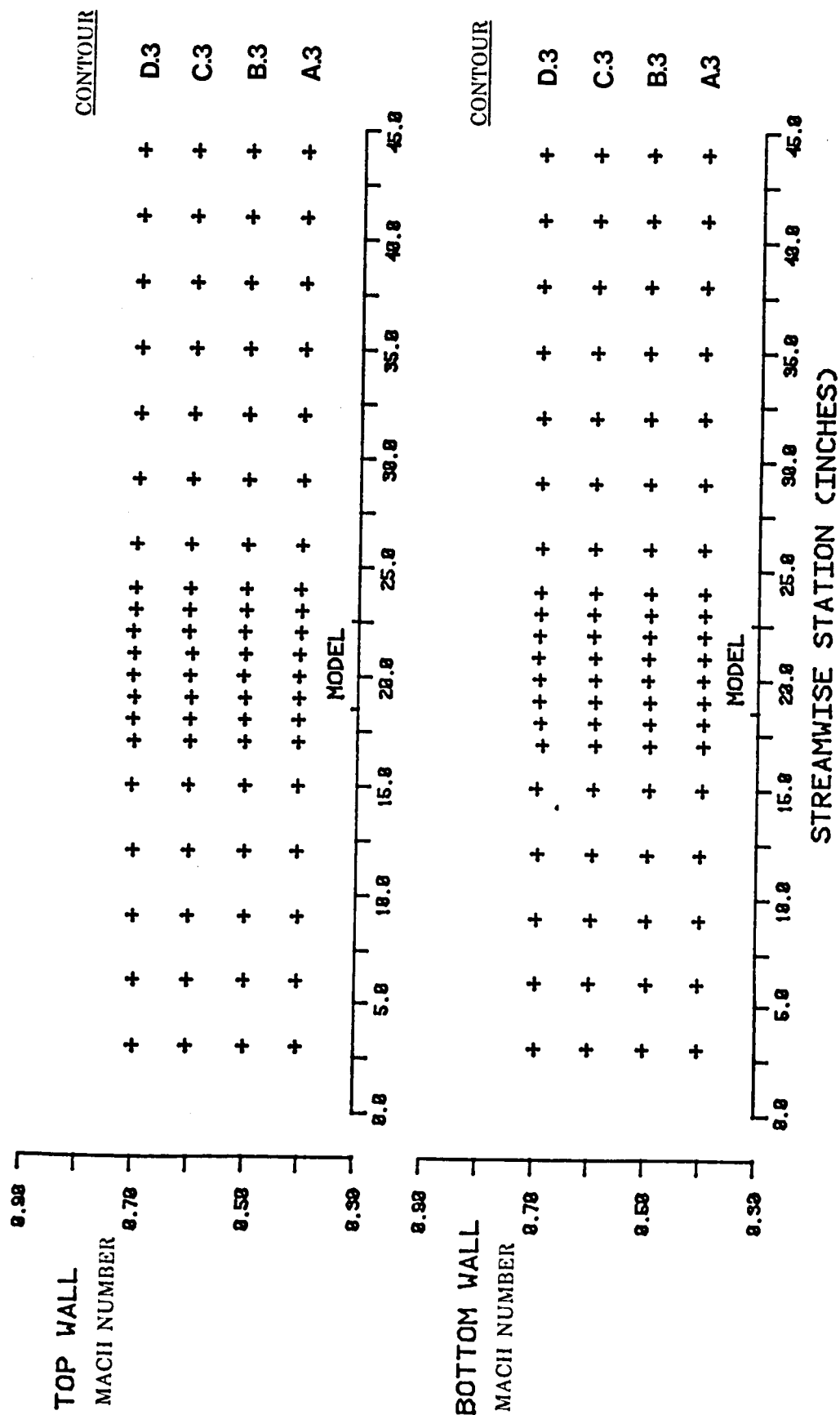


FIG. 8.3 NACA 0012-64 MEASUREMENTS ($\alpha \approx 4.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF WALLS SET TO CONSTANT PRESSURE CONTOURS

**FIG. 9 SELECTED WALL CONTOURS. WALLS SET TO AERODYNAMICALLY
STRAIGHT, CONSTANT PRESSURE AND STREAMLINED CONTOURS**

Note: *"STRAIGHT"* refers to aerodynamically straight.

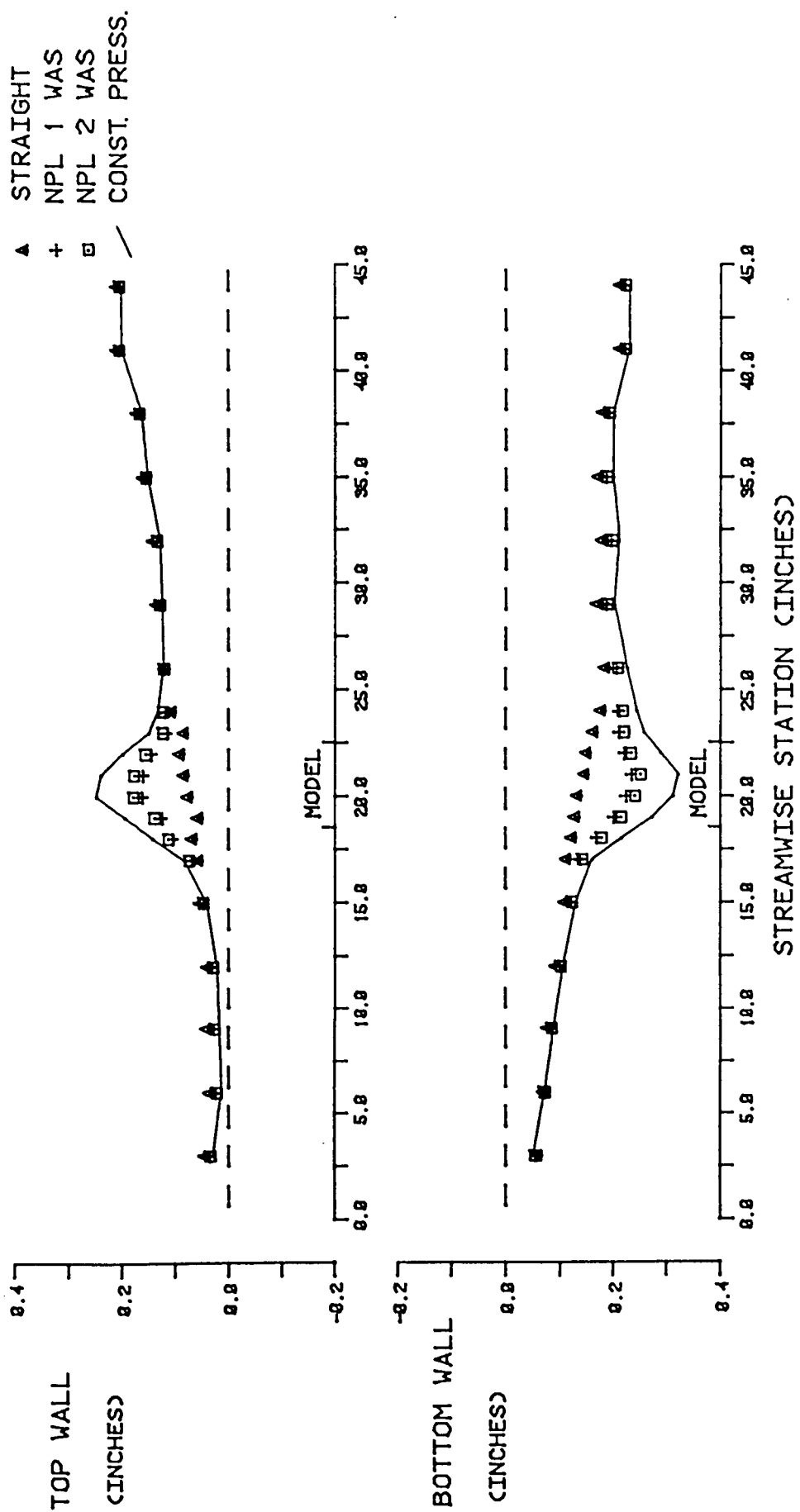


FIG.9.1 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.8$, $\alpha \approx 0.5^\circ$). DISPLACEMENTS OF WALLS FROM GEOMETRICALLY STRAIGHT CONTOURS

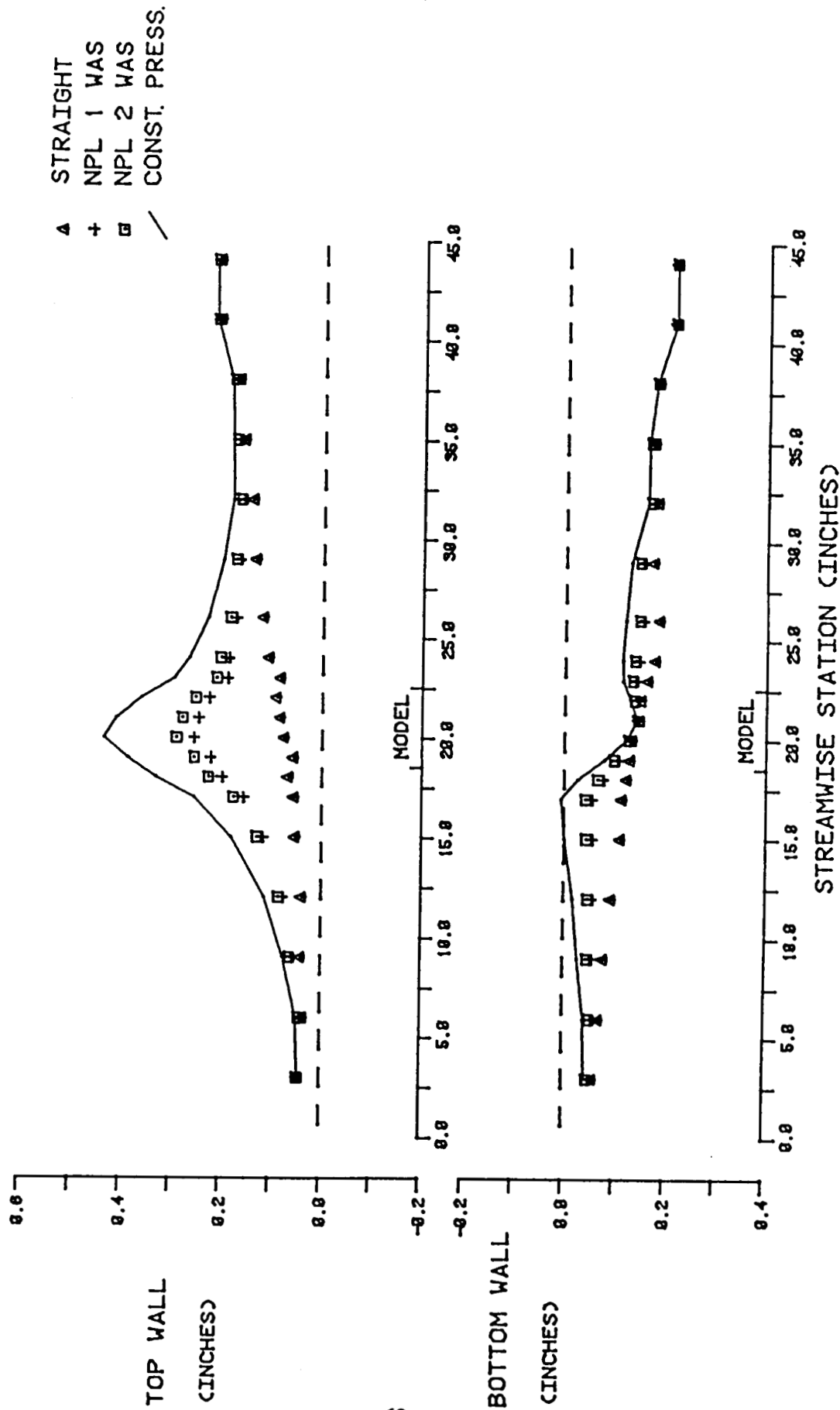


FIG.9.2 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.8$, $\alpha = 2.0^\circ$). DISPLACEMENTS OF WALLS FROM GEOMETRICALLY STRAIGHT CONTOURS

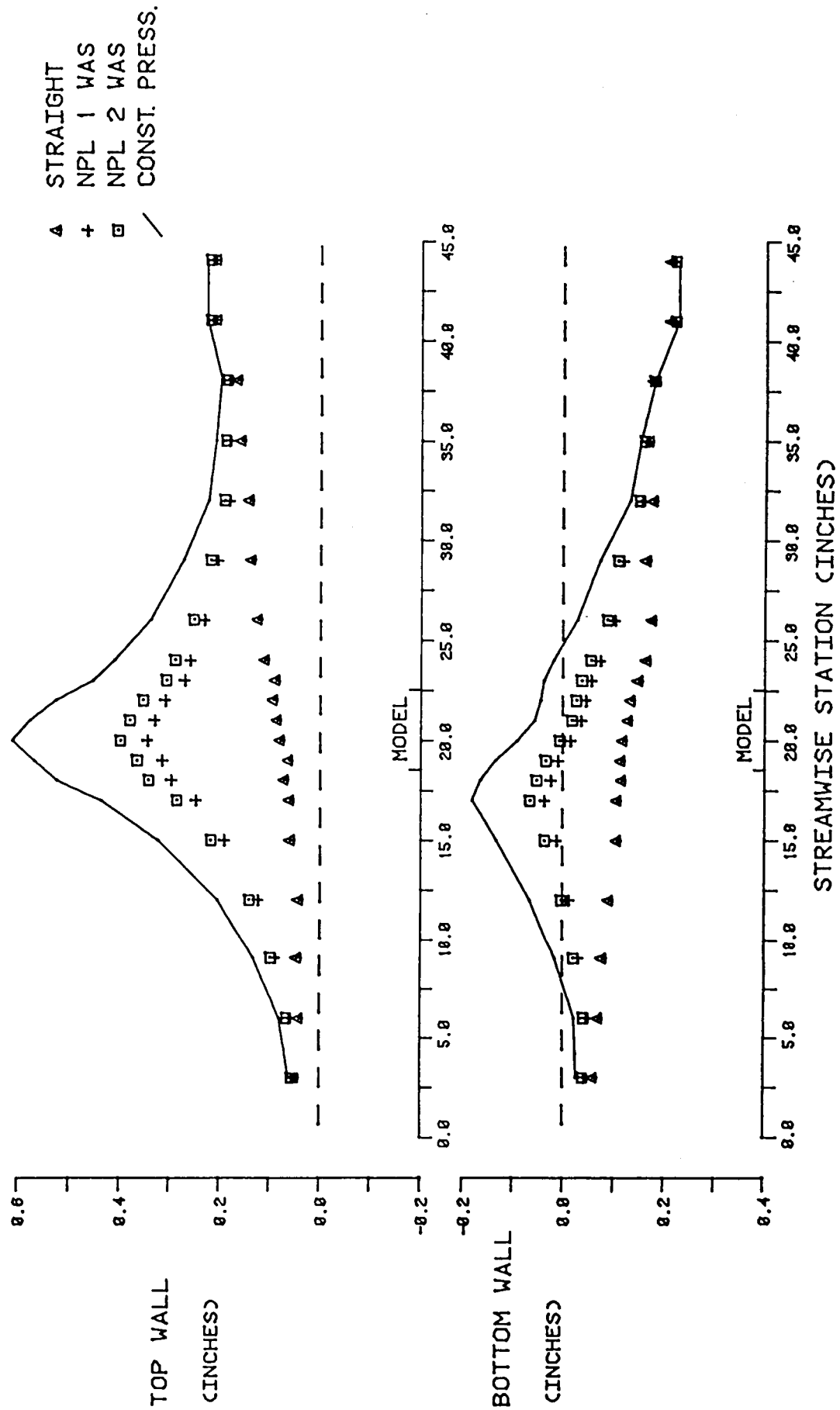


FIG.9.3 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.7$, $\alpha = 4.0^\circ$). DISPLACEMENTS OF WALLS FROM GEOMETRICALLY STRAIGHT CONTOURS

**FIG.10 SELECTED AEROFOIL PRESSURE DISTRIBUTIONS. WALLS SET TO
AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND
STREAMLINED (NPL WAS) CONTOURS**

Note: 1) See Section 11 for definition of CP, CP*, CL, CD and CM.

2) "*STRAIGHT*" refers to aerodynamically straight.

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
21 2.0° 0.700

TRANSITION FIXED

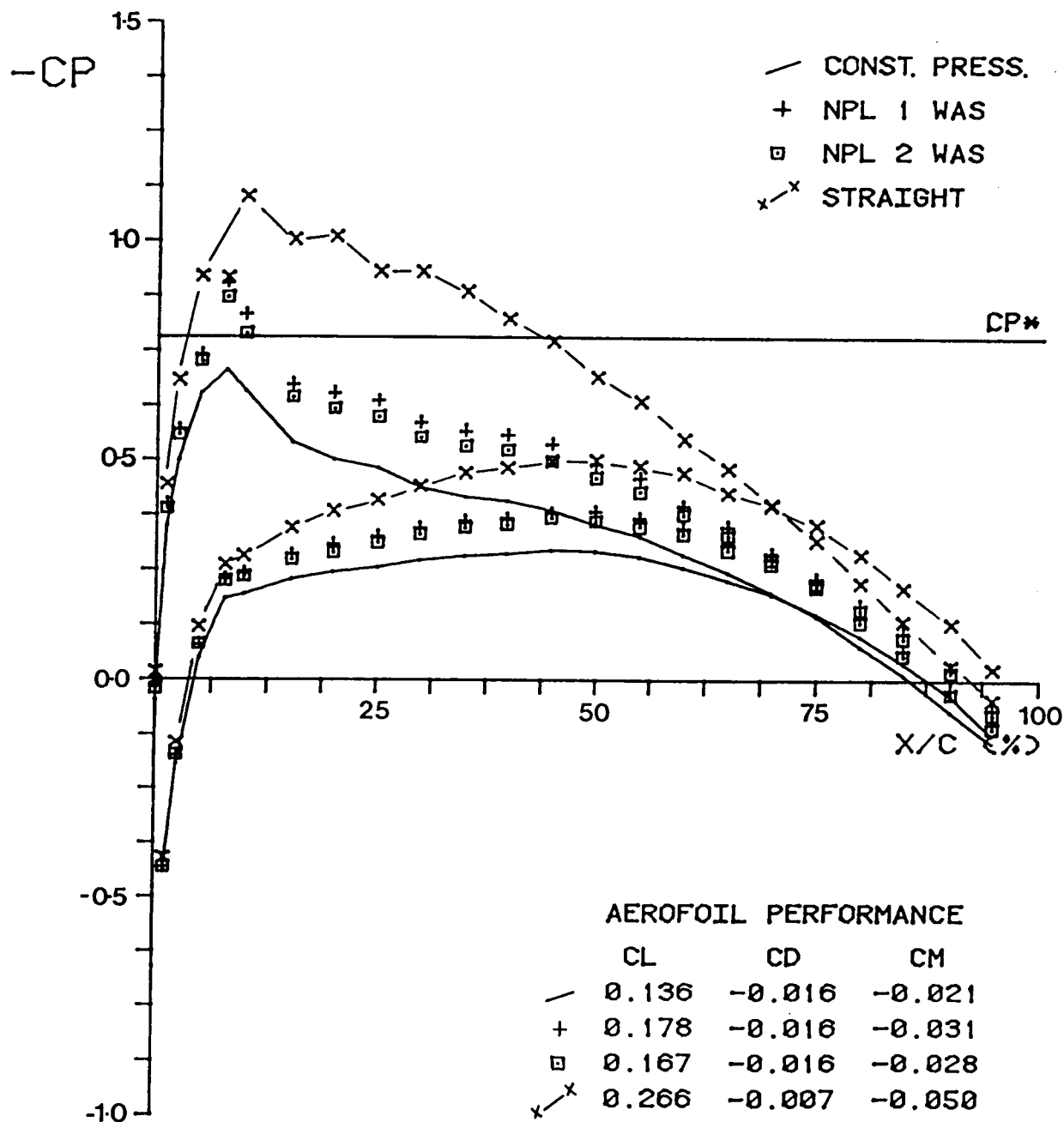


FIG.10.1 MODEL PRESSURE DISTRIBUTIONS. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED (NPL WAS) CONTOURS

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
5 4.0° 0.600

TRANSITION FIXED

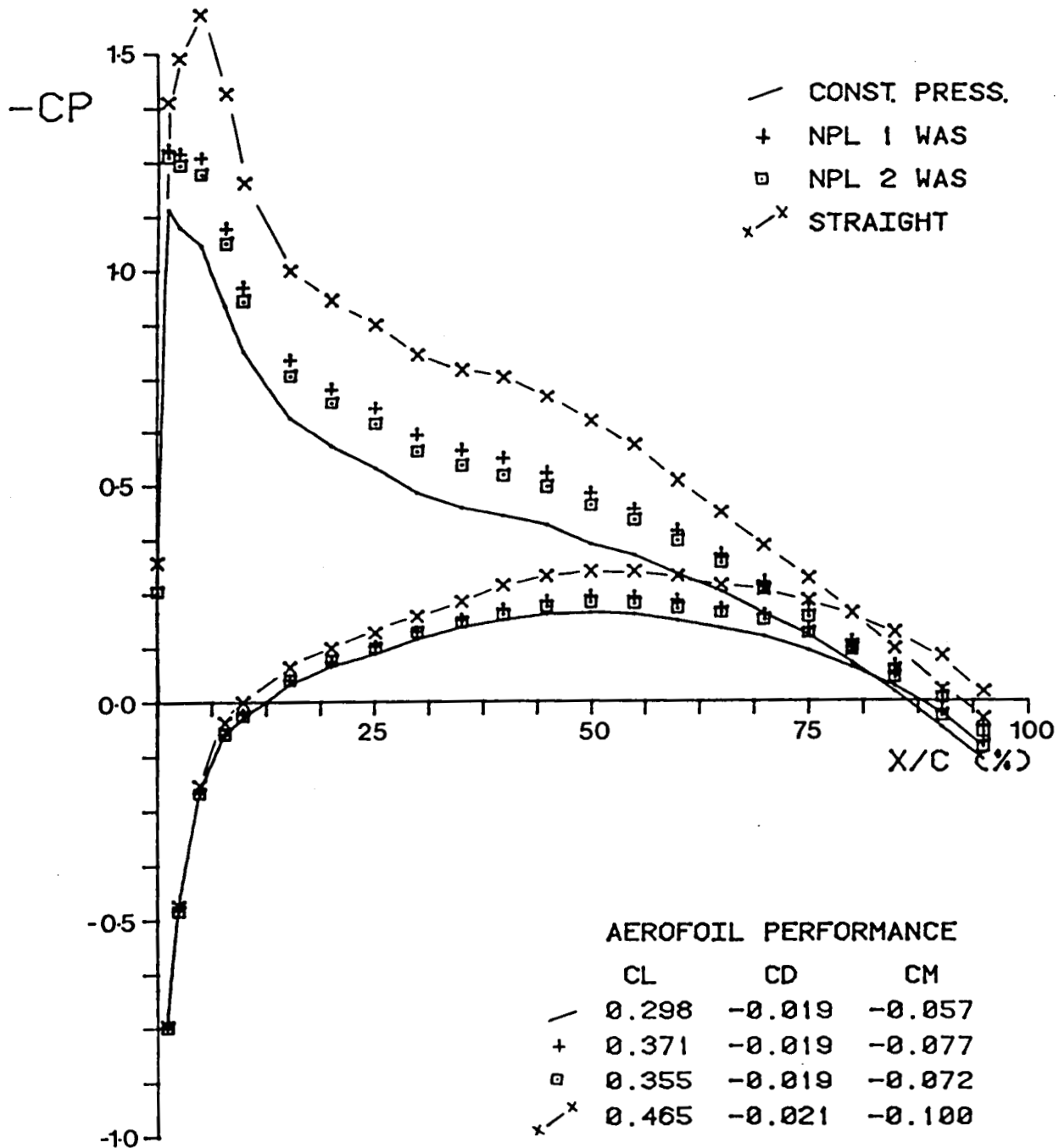


FIG.10.2 MODEL PRESSURE DISTRIBUTIONS. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED (NPL WAS) CONTOURS

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
6 4.0° 0.700

TRANSITION FIXED

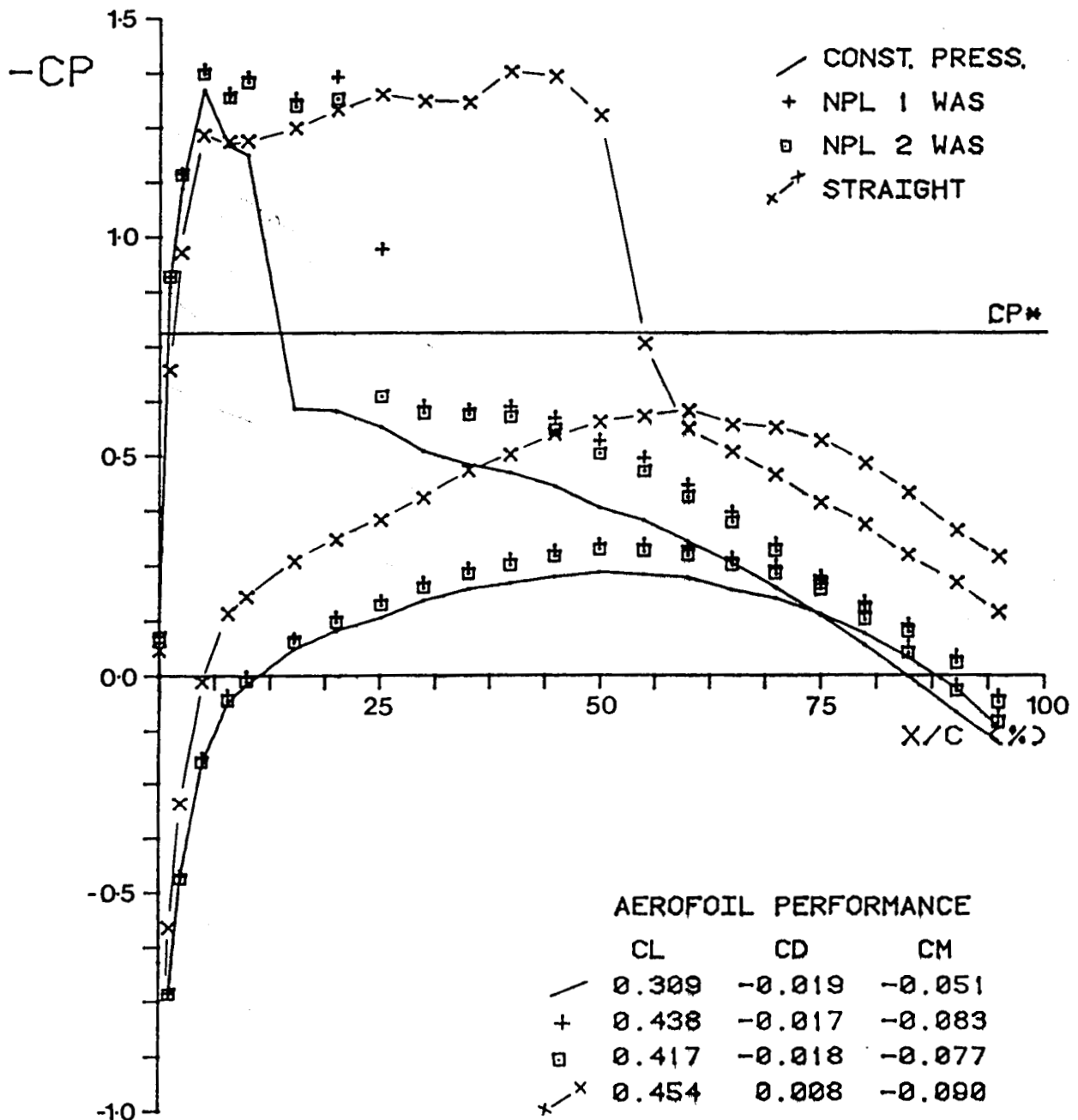


FIG.10.3 MODEL PRESSURE DISTRIBUTIONS. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED (NPL WAS) CONTOURS

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OF POOR QUALITY

NACA 0012-64 SECTION

$M_{\infty}=0.7$; $\alpha = 4.0^{\circ}$



Straight Walls



Streamlined Walls (WAS 1)

FIG. 11 SCHLIEREN PICTURES ILLUSTRATING THE EFFECTS OF
WALL STREAMLINING

FIG.12 SELECTED WALL MACH NUMBER DISTRIBUTIONS. WALLS SET TO
AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS.

Note:- "*STRAIGHT*" refers to aerodynamically straight.

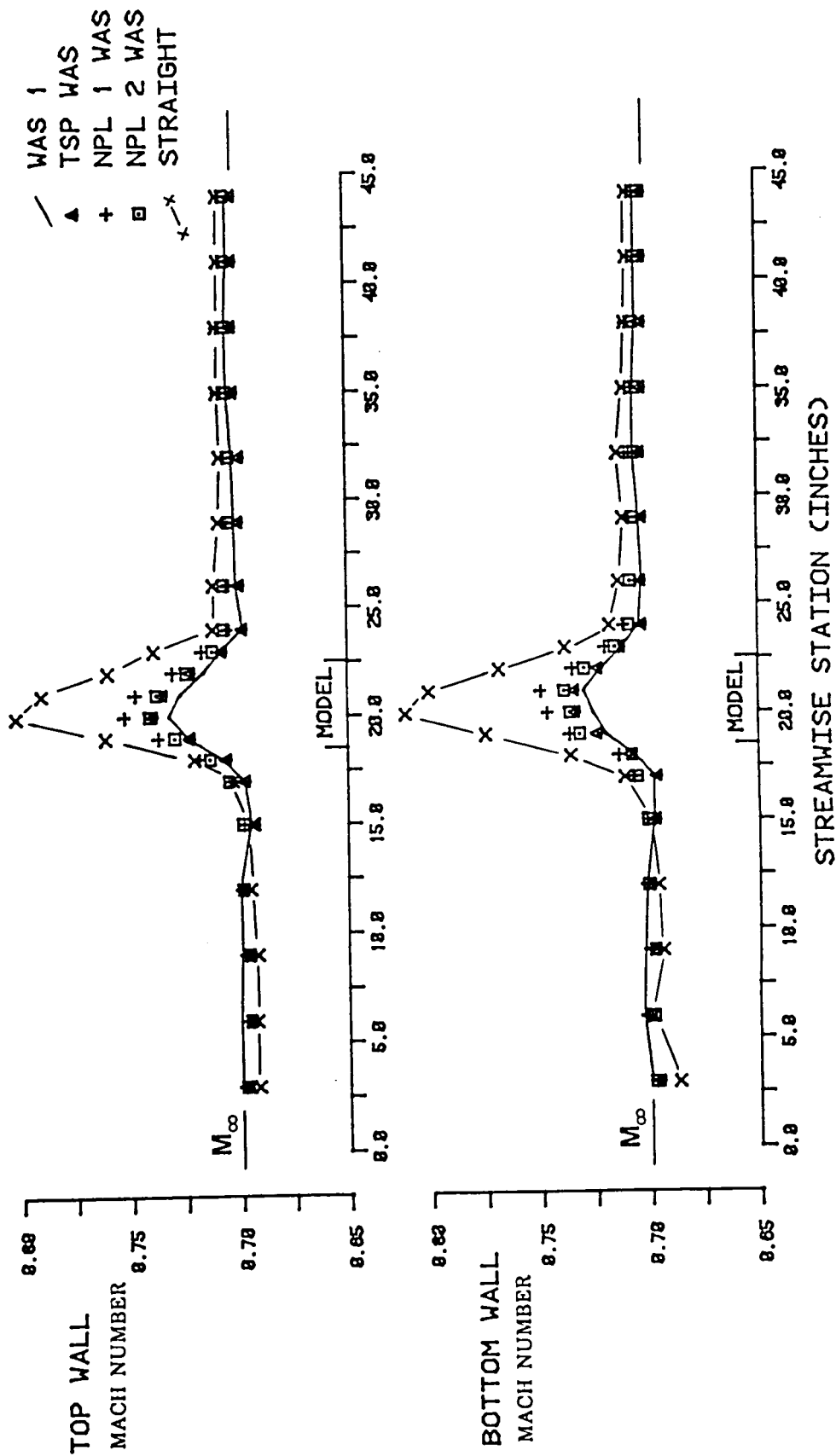


FIG.12.1 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.7$, $\alpha = 0.5^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS

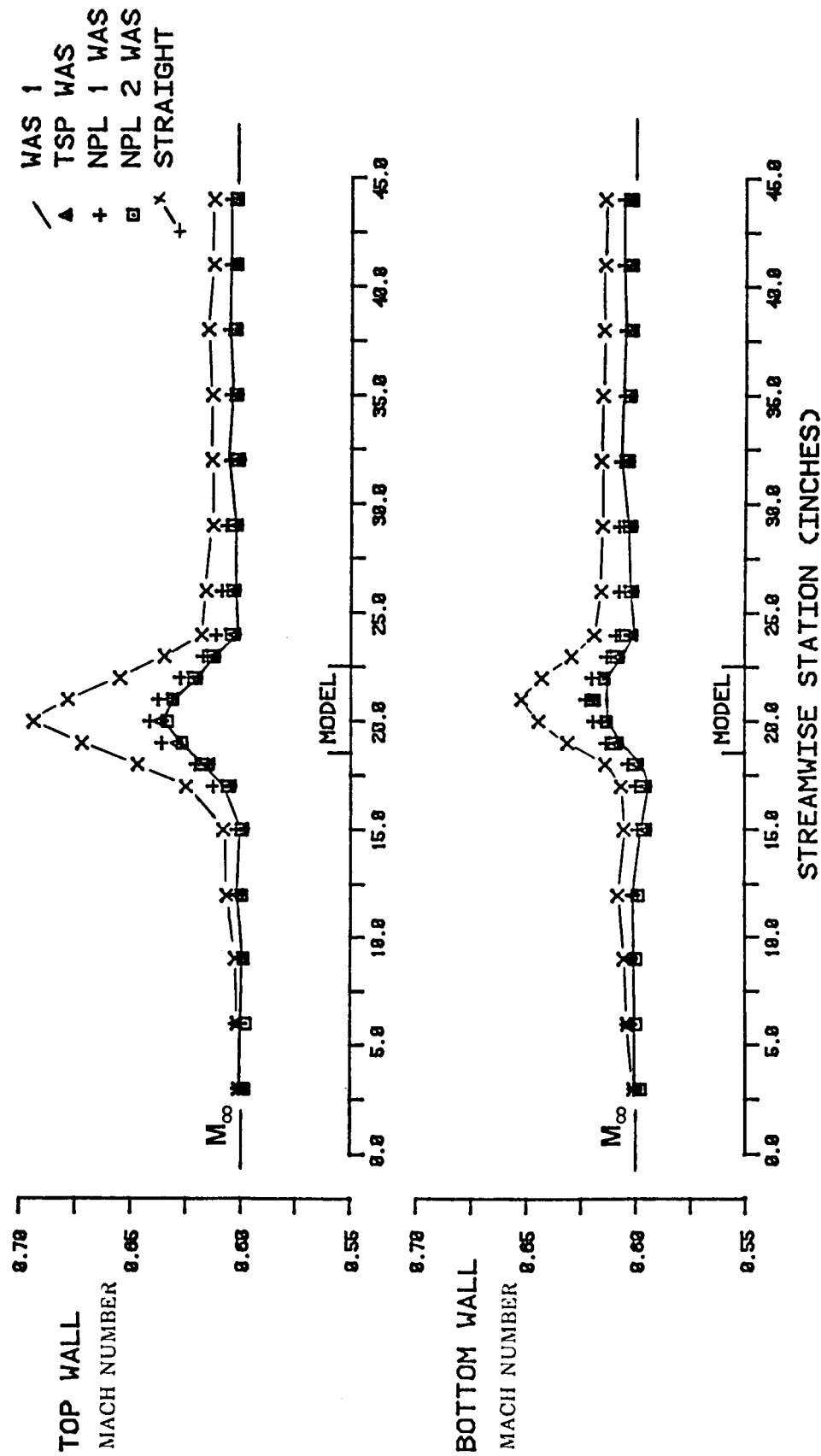


FIG.12.2 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.6$, $\alpha \approx 2.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS

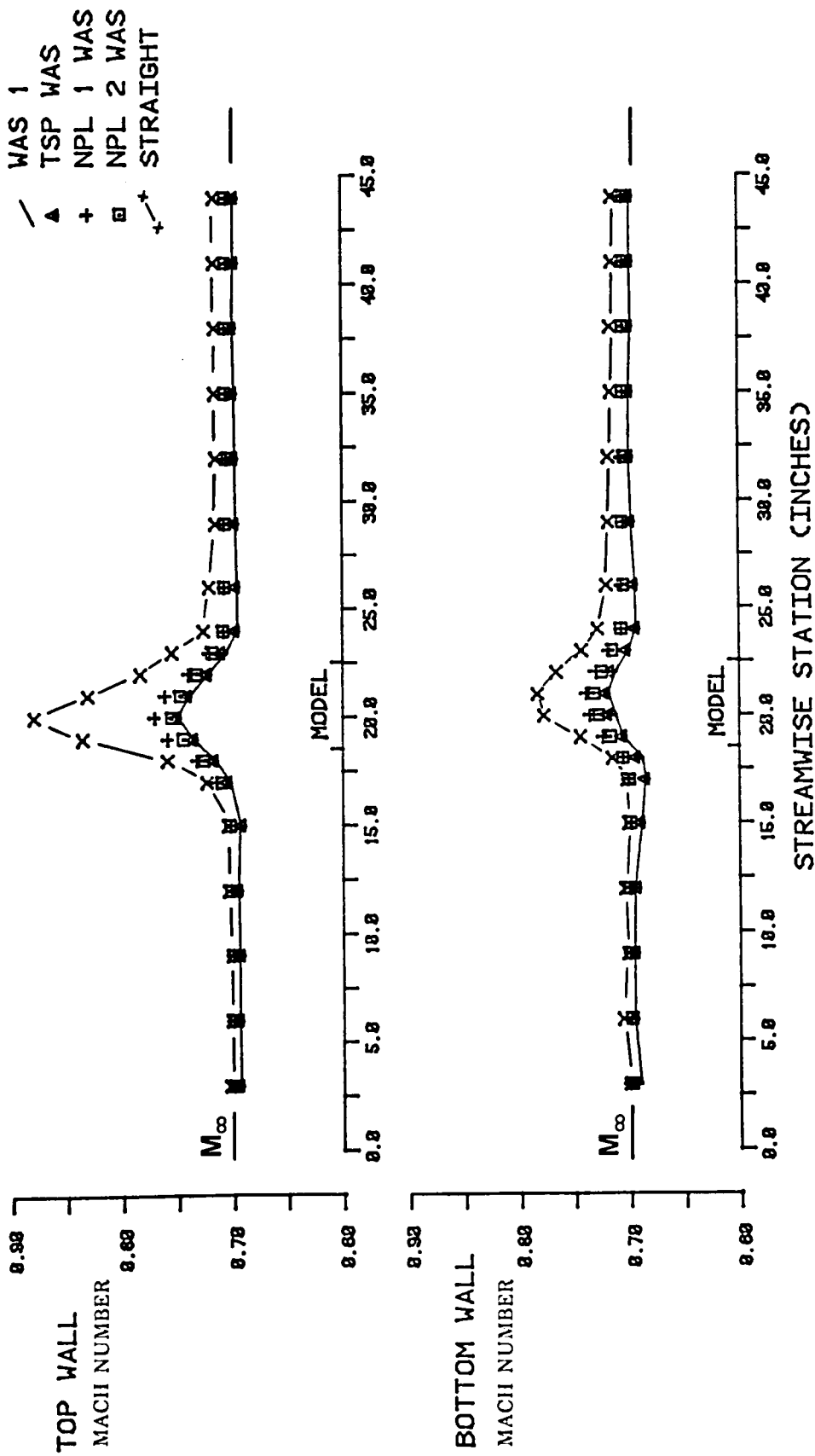


FIG.12.3 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.7$, $\alpha = 2.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS

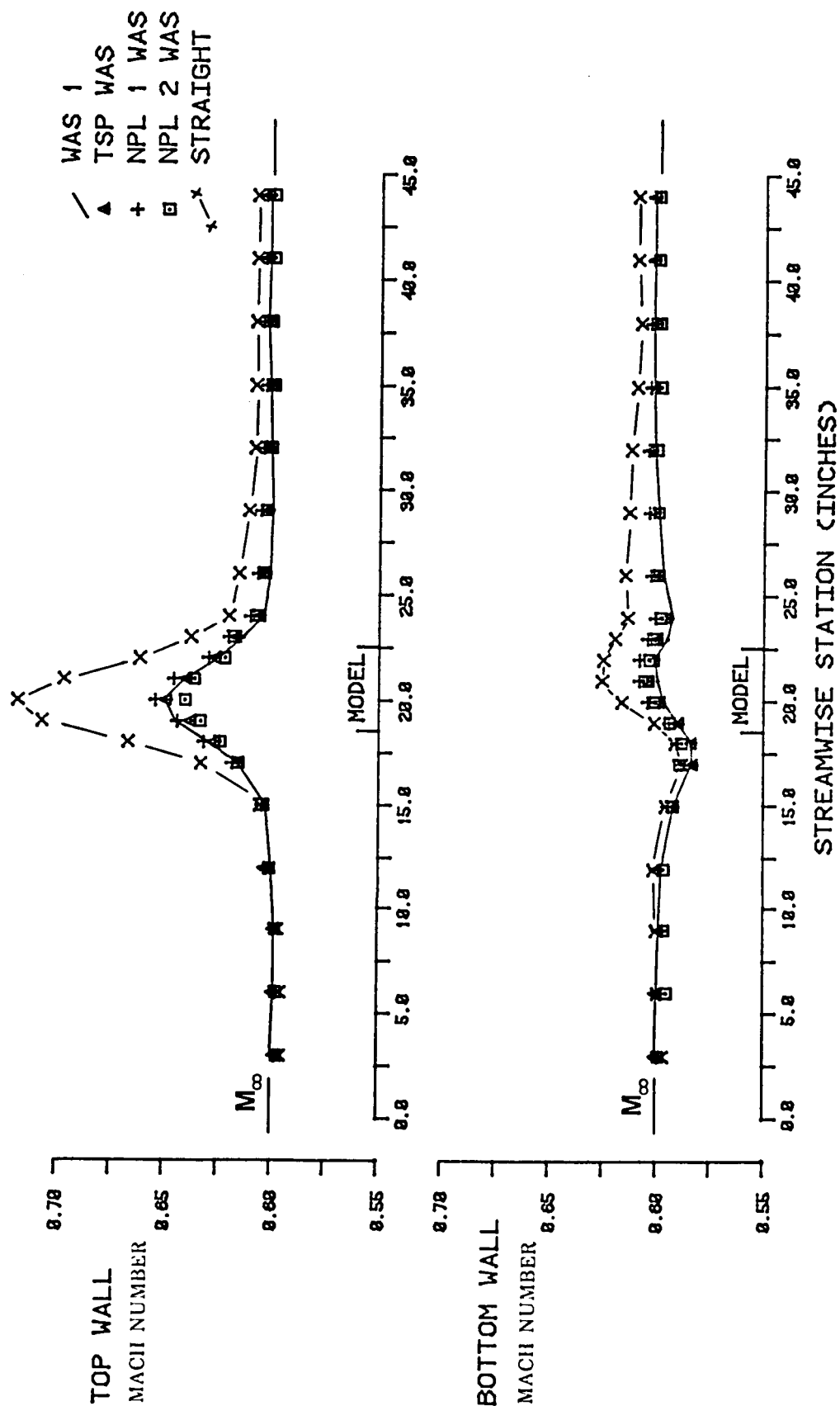


FIG.12.4 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.6$, $\alpha = 4.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS

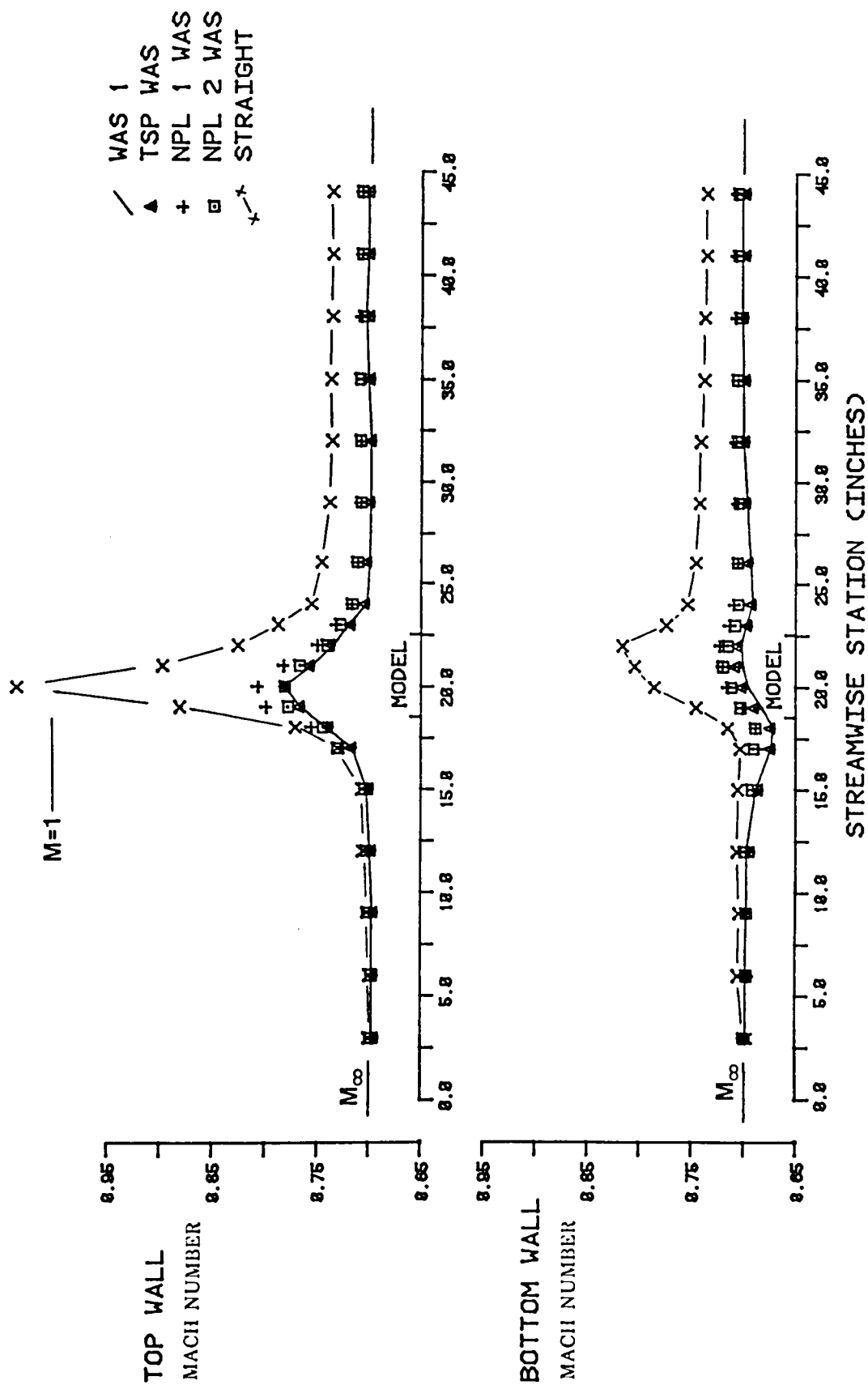


FIG.12.5 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.7$, $\alpha = 4.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF AERODYNAMICALLY STRAIGHT AND STREAMLINED CONTOURS

FIG.13 SELECTED STREAMLINED WALL CONTOURS

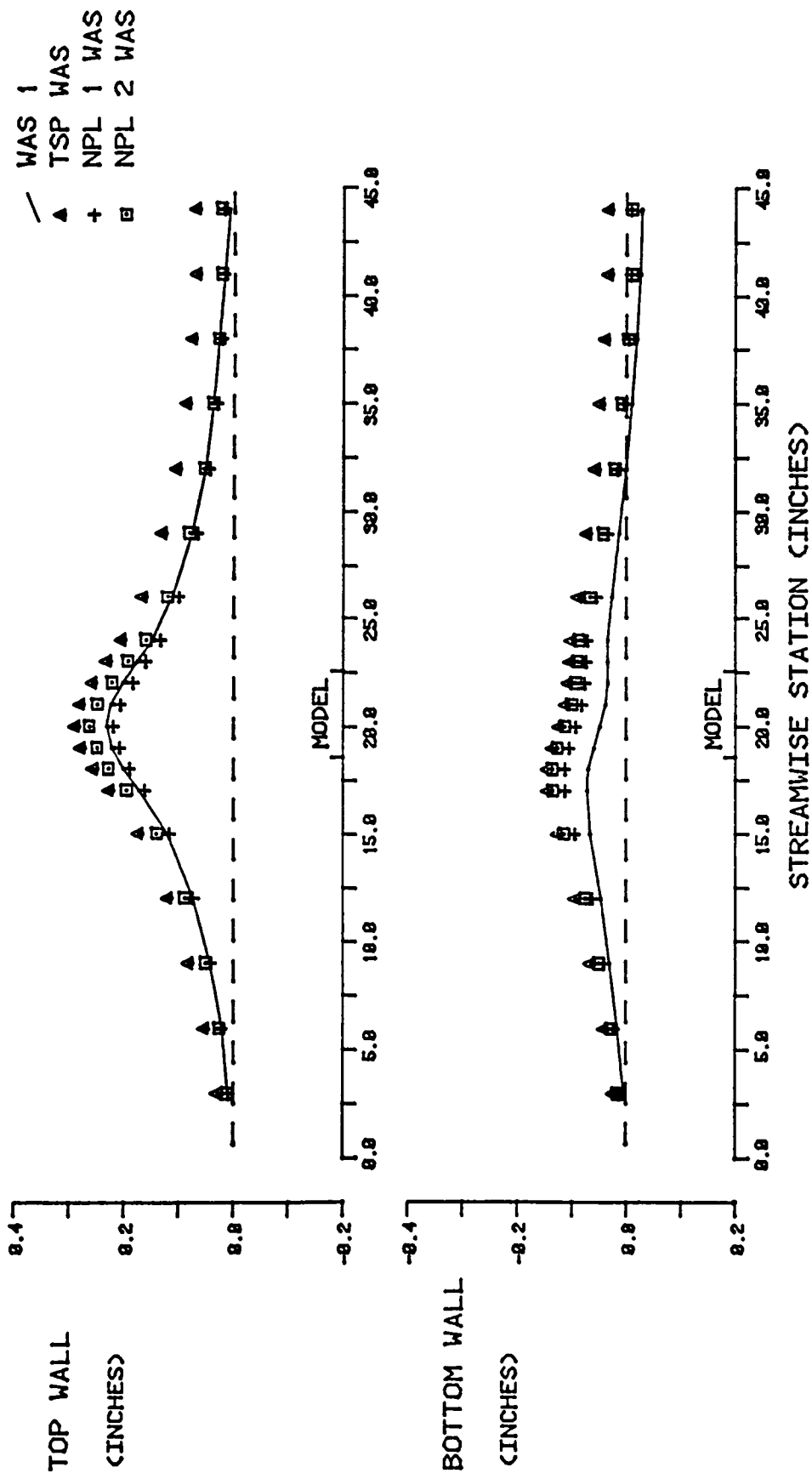


FIG.13.1.1 NACA 0012-64 MEASUREMENTS. DISPLACEMENTS OF WALLS FROM AERODYNAMICALLY STRAIGHT CONTOURS.
WALLS STREAMLINED AT $M_\infty = 0.4$; $\alpha = 4.0^\circ$

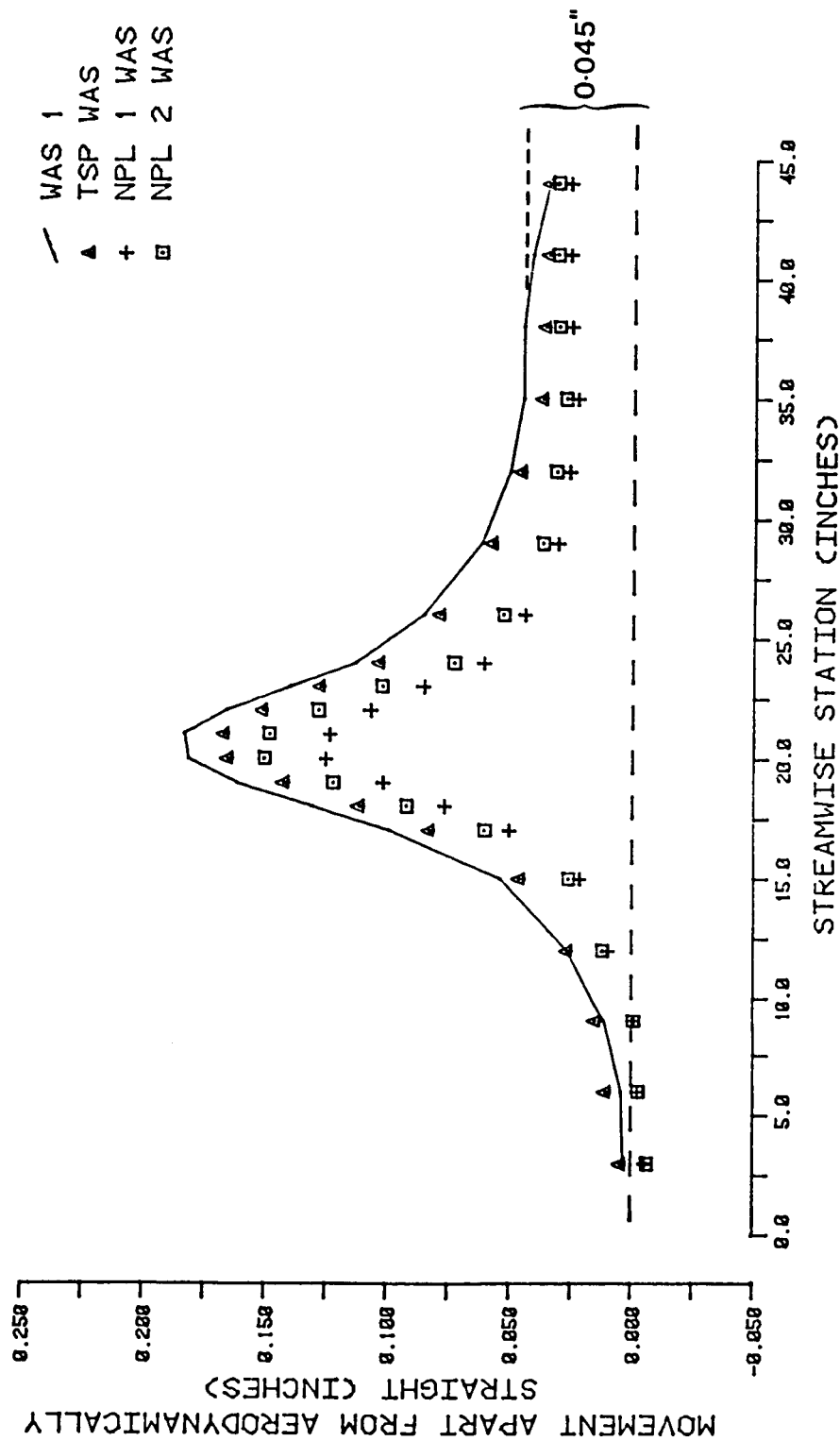


FIG.13.1.2 NACA 0012-64 MEASUREMENTS. WALL MOVEMENTS APART FROM AERODYNAMICALLY STRAIGHT CONTOURS. WALLS STREAMLINED AT $M_\infty = 0.4$; $\alpha \approx 4.0^\circ$

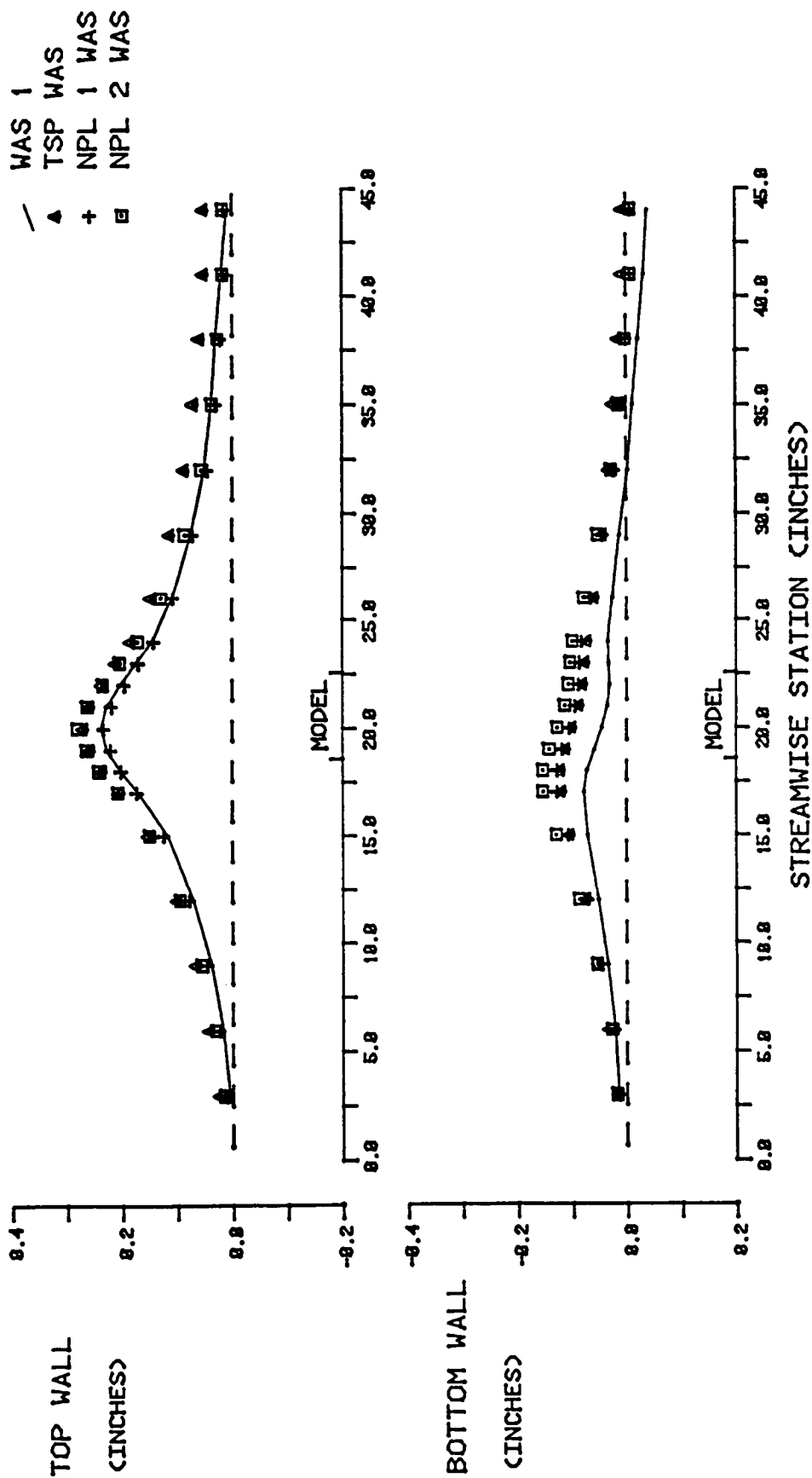


FIG.13.2.1 NACA 0012-64 MEASUREMENTS. DISPLACEMENTS OF WALLS FROM AERODYNAMICALLY STRAIGHT CONTOURS.
WALLS STREAMLINED AT $M_\infty = 0.5$; $\alpha \approx 4.0^\circ$

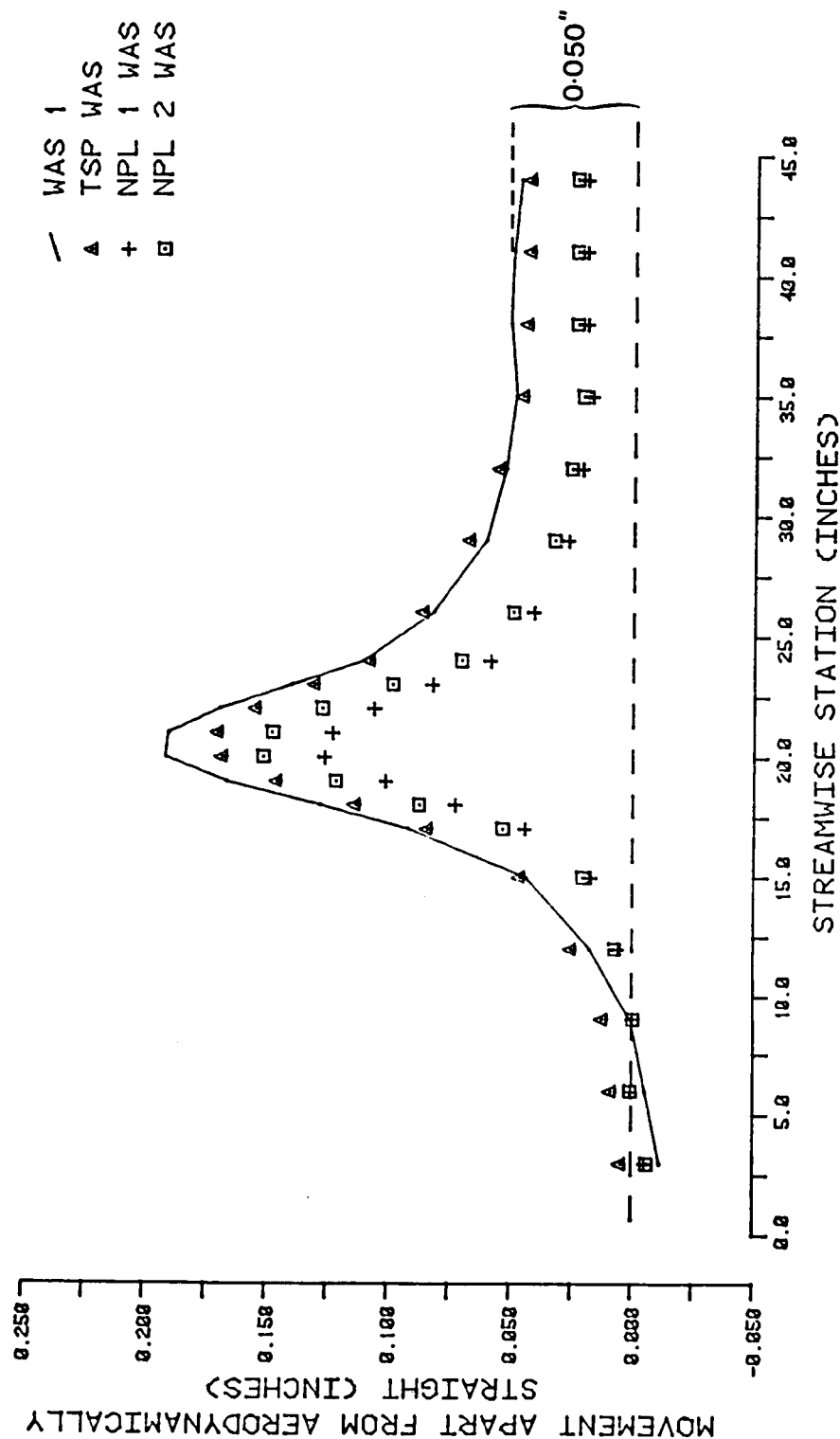


FIG. 13.2.2 NACA 0012-64 MEASUREMENTS. WALL MOVEMENTS APART FROM AERODYNAMICALLY STRAIGHT CONTOURS.
WALLS STREAMLINED AT $M_\infty = 0.5$, $\alpha \approx 4.0^\circ$

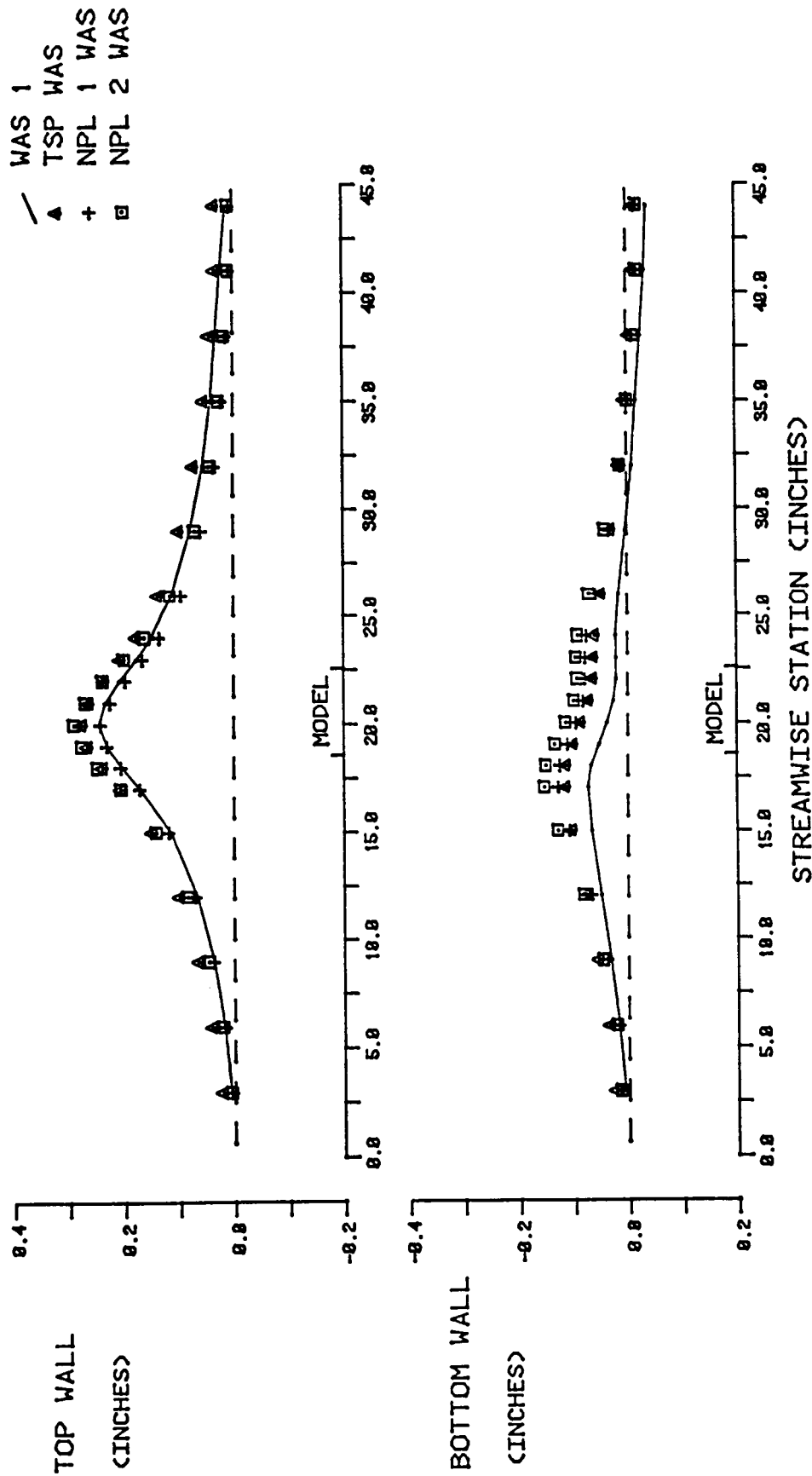


FIG.13.3.1 NACA 0012-64 MEASUREMENTS. DISPLACEMENTS OF WALLS FROM AERODYNAMICALLY STRAIGHT CONTOURS.
WALLS STREAMLINED AT $M_\infty = 0.6$; $\alpha \approx 4.0^\circ$

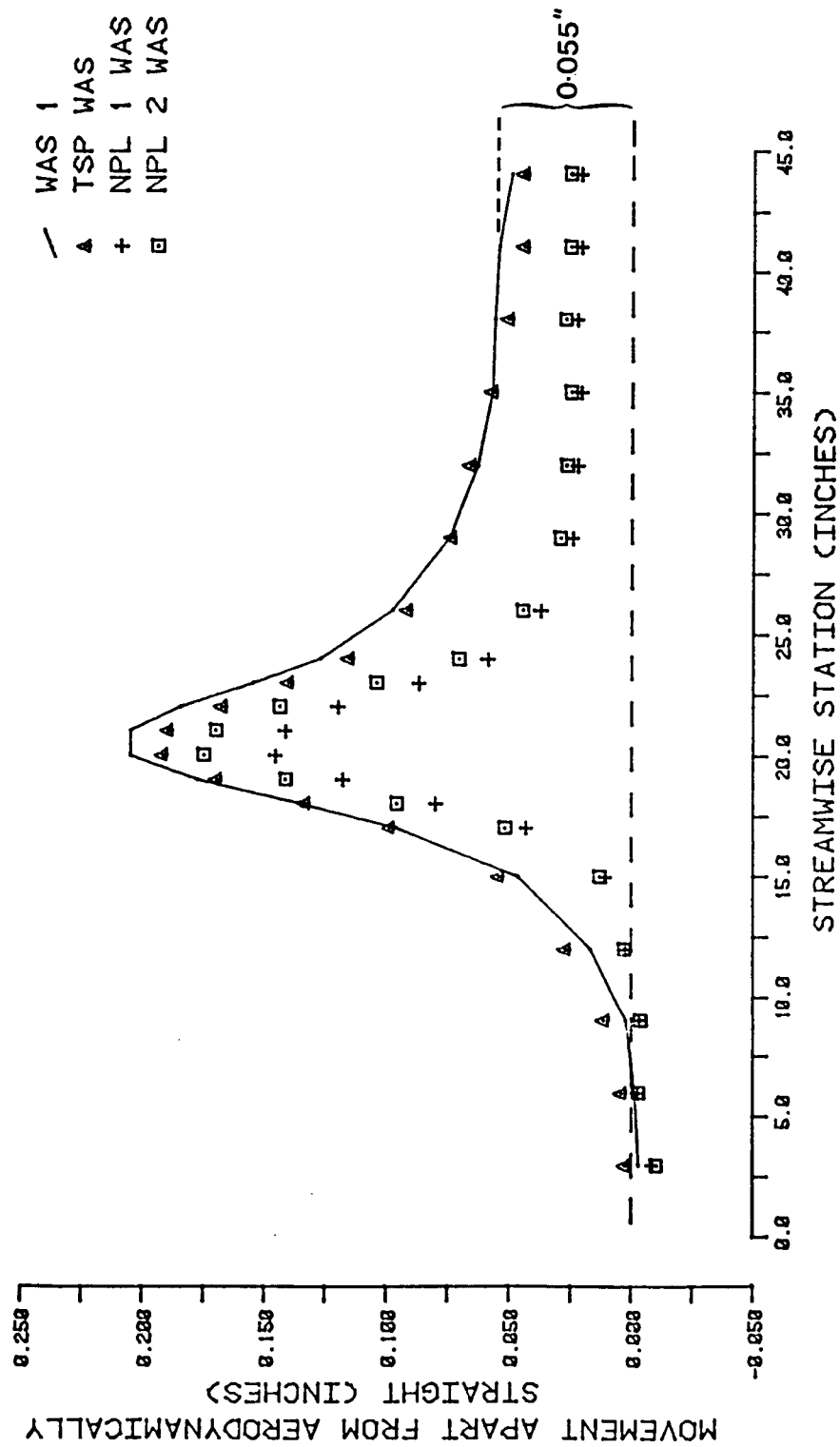


FIG.13.3.2 NACA 0012-64 MEASUREMENTS. WALL MOVEMENTS APART FROM AERODYNAMICALLY STRAIGHT CONTOURS. WALLS STREAMLINED AT $M_\infty = 0.6$; $\alpha \approx 4.0^\circ$

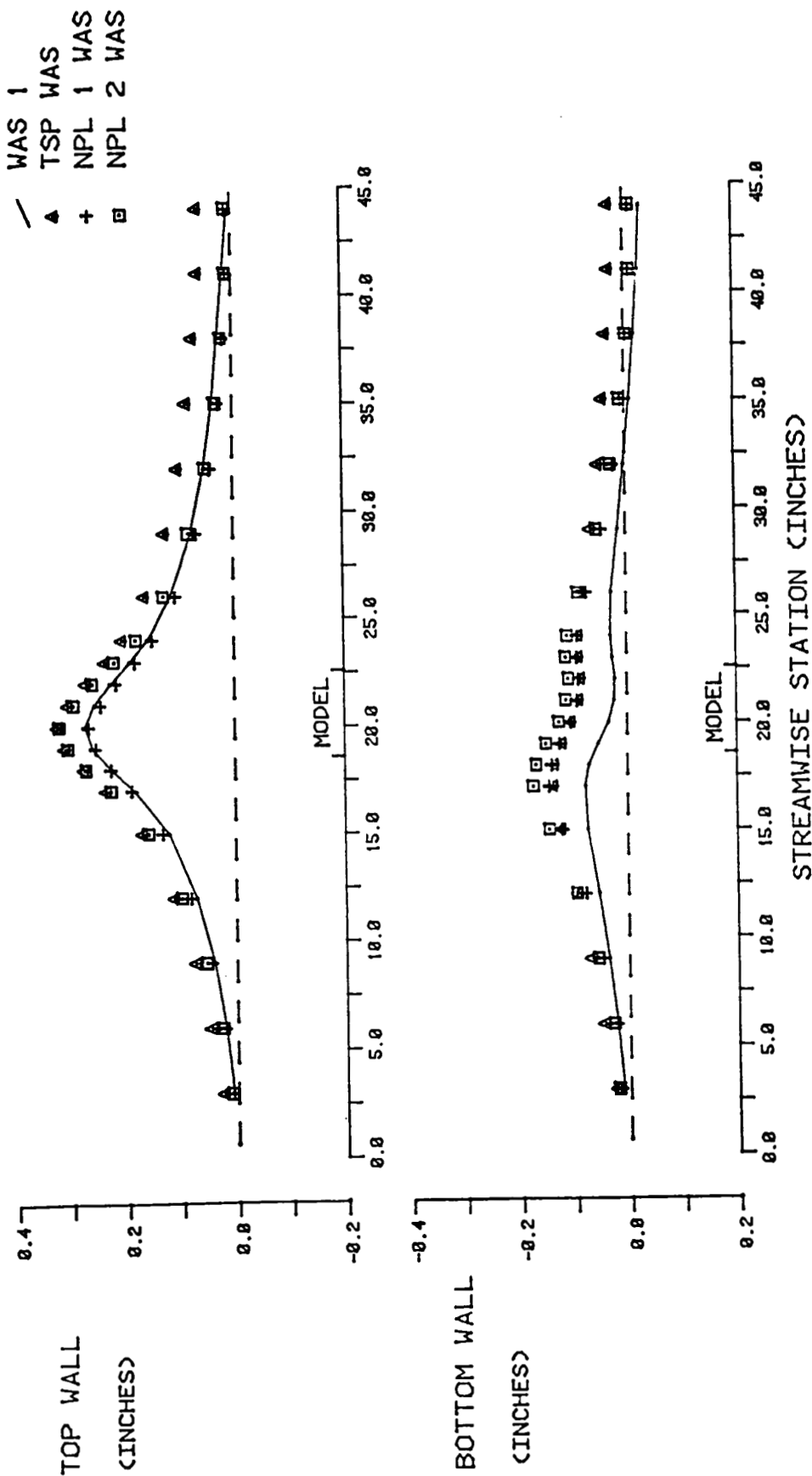


FIG.13.4.1 NACA 0012-64 MEASUREMENTS. DISPLACEMENTS OF WALLS FROM AERODYNAMICALLY STRAIGHT CONTOURS.
WALLS STREAMLINED AT $M_\infty = 0.7$; $\alpha = 4.0^\circ$

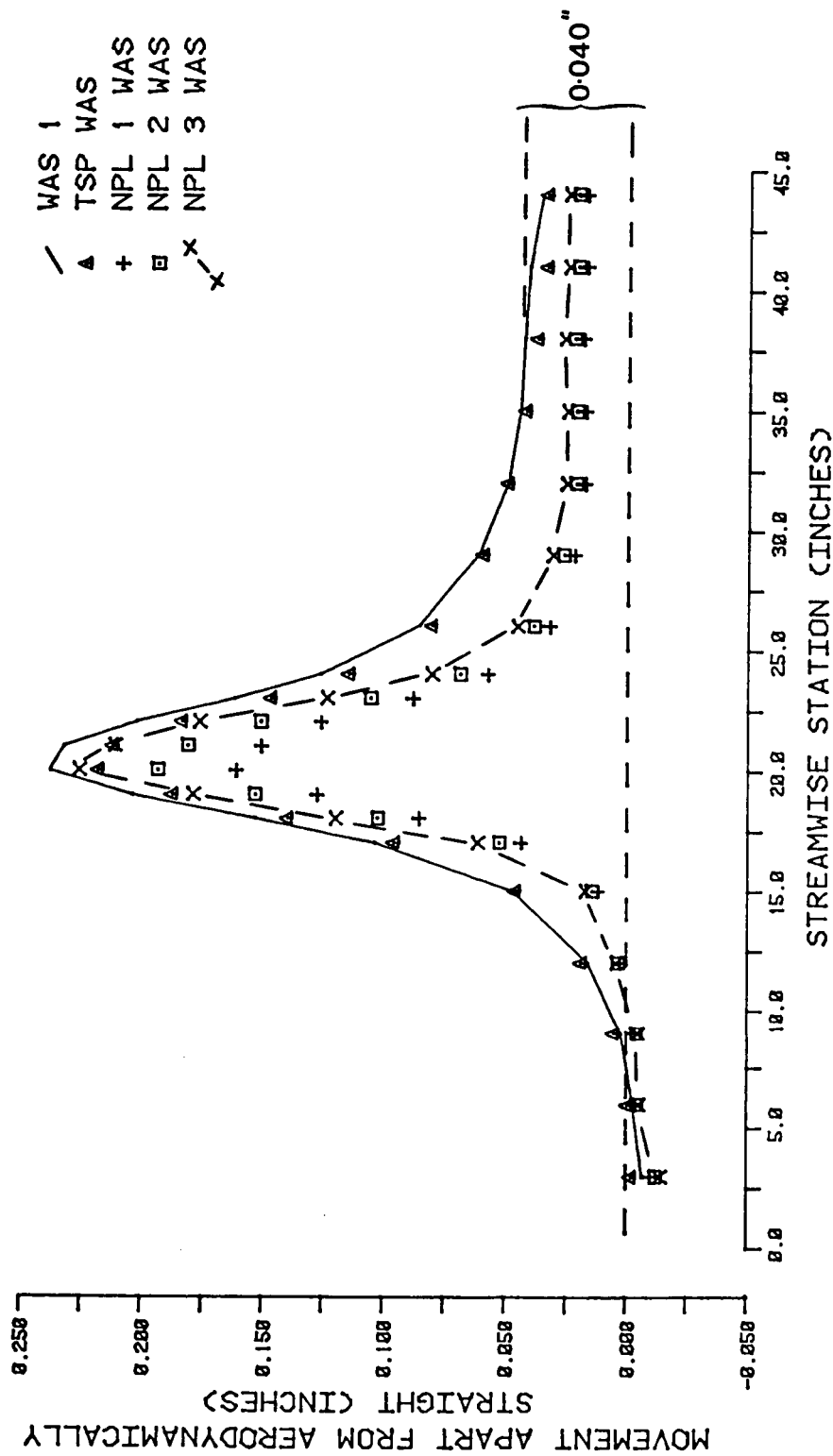


FIG.13.4.2 NACA 0012-64 MEASUREMENTS. WALL MOVEMENTS APART FROM AERODYNAMICALLY STRAIGHT CONTOURS. WALLS STREAMLINED AT $M_\infty = 0.7$, $\alpha \approx 4.0^\circ$

**FIG.14 MODEL PRESSURE DISTRIBUTIONS. WALLS SET TO STREAMLINED
CONTOURS**

Note:- See Section 11 for definition of CP, CP*, CL, CD and CM.

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
41 0.5° 0.400

TRANSITION FIXED

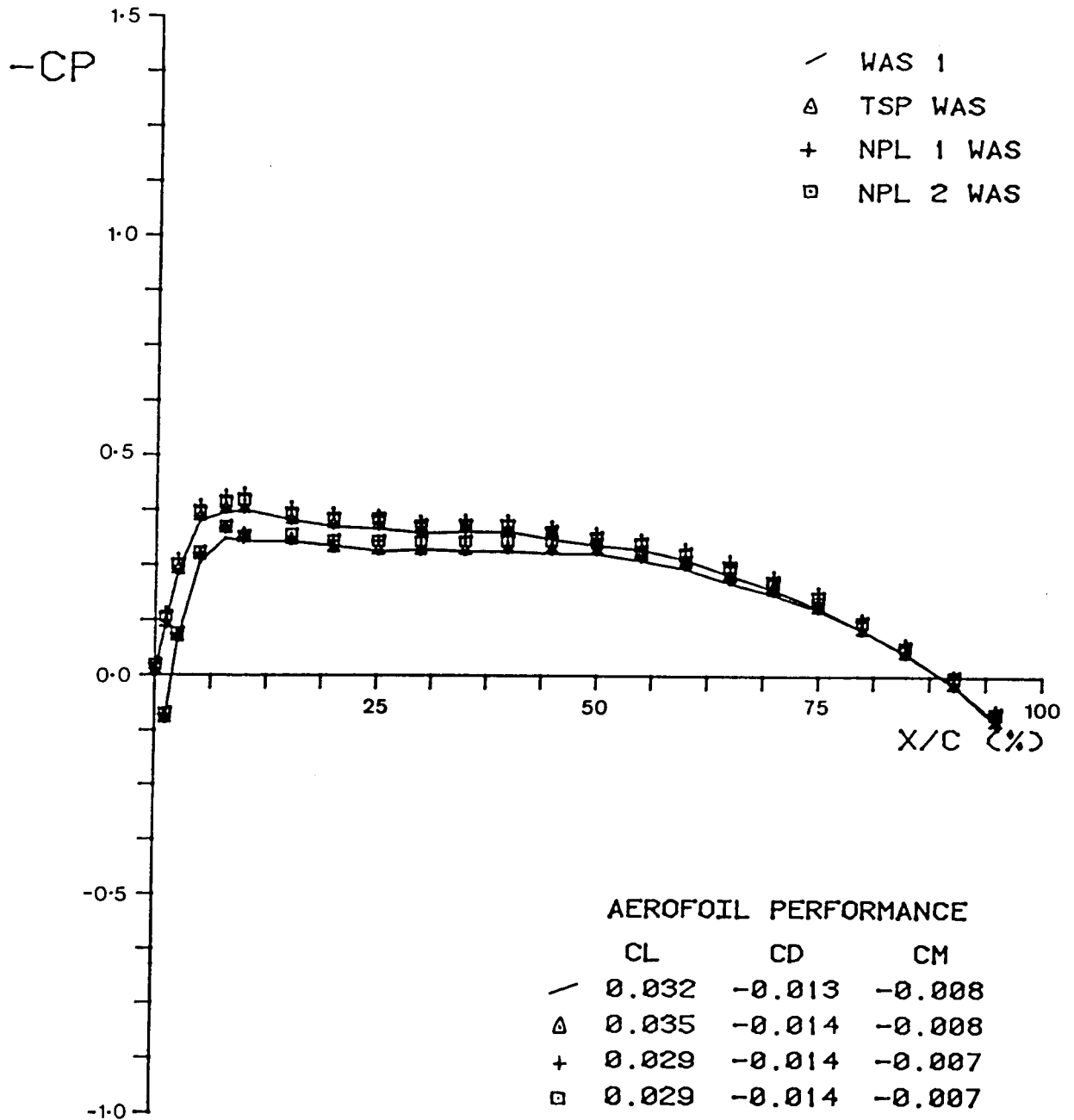
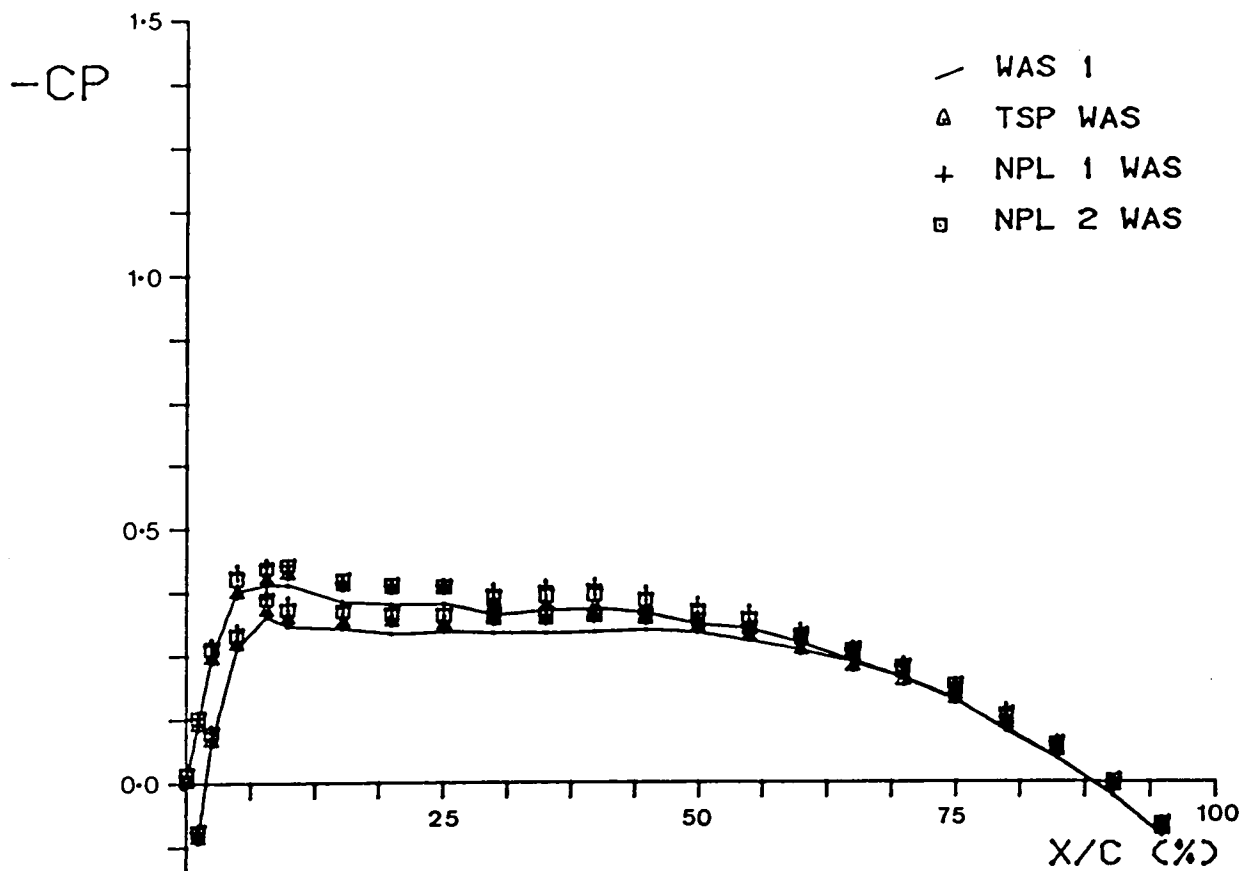


FIG.14.1

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
40 0.5° 0.500

TRANSITION FIXED



AEROFOIL PERFORMANCE			
	CL	CD	CM
—	0.033	-0.014	-0.007
△	0.033	-0.014	-0.007
+	0.031	-0.014	-0.006
□	0.034	-0.014	-0.008

FIG.14.2

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
39 0.5° 0.600

TRANSITION FIXED

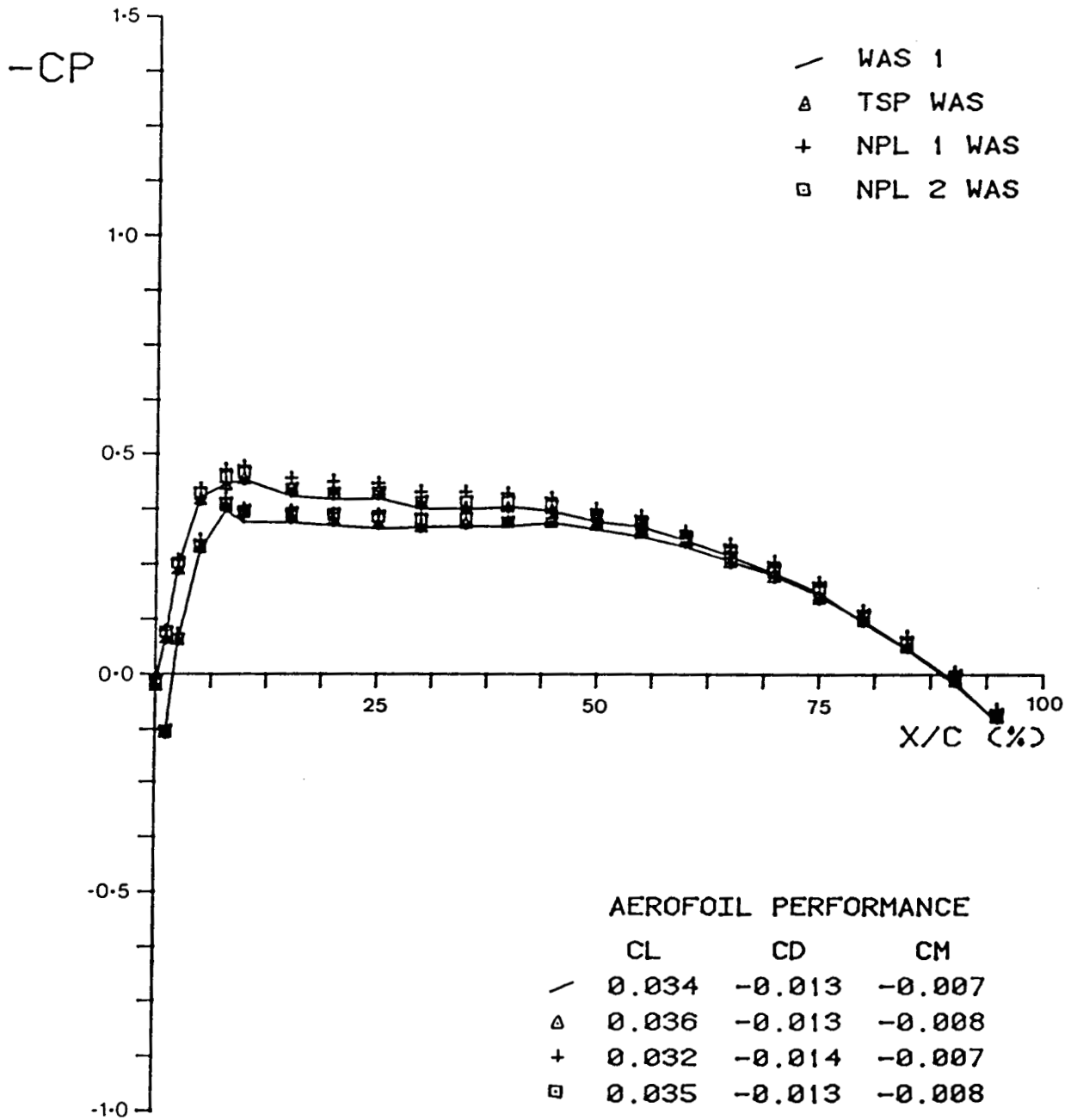


FIG.14.3

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
42 0.5° 0.700

TRANSITION FIXED

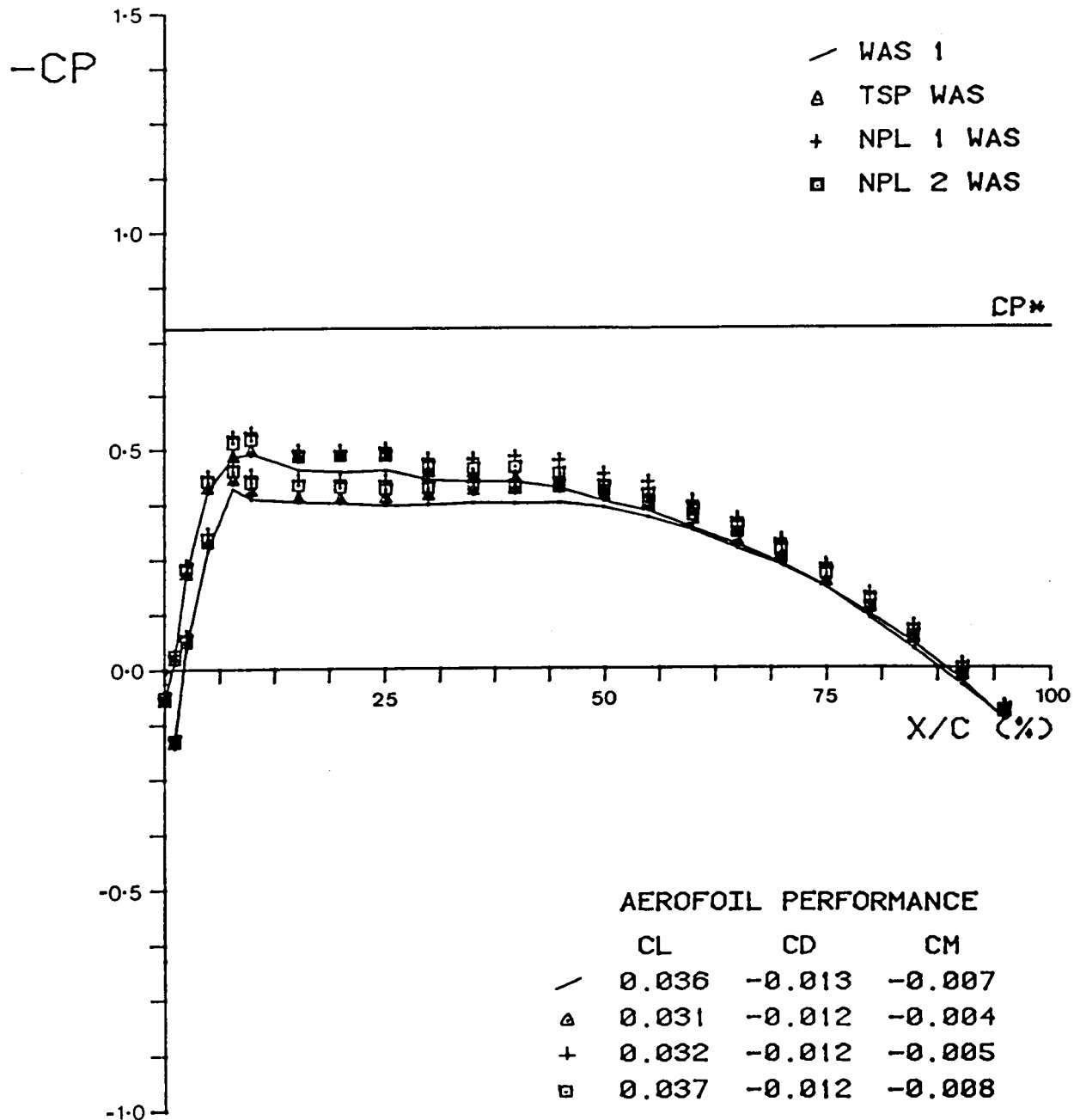


FIG.14.4

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
43 0.5° 0.800

TRANSITION FIXED

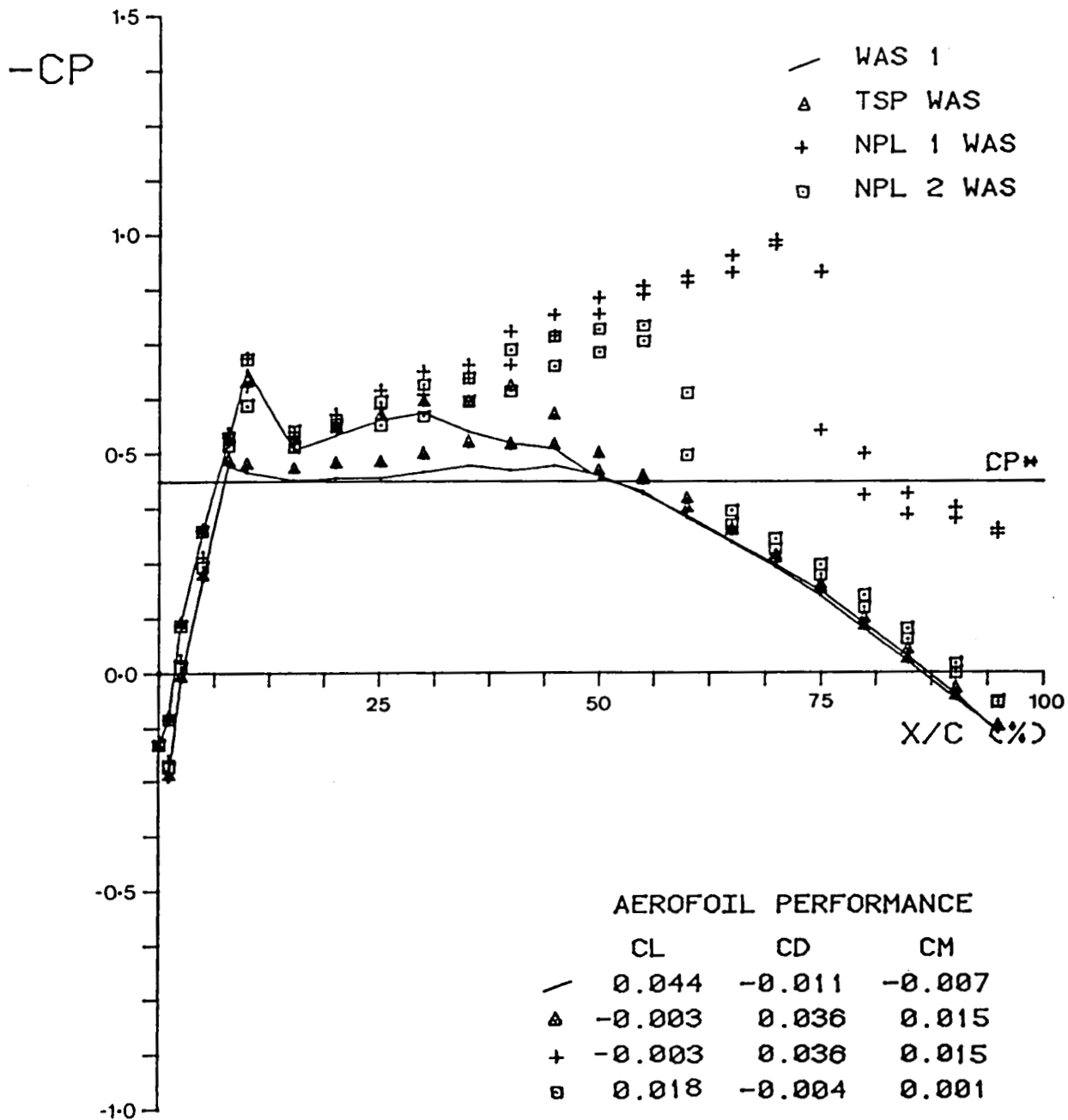


FIG.14.5

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
35 2.0° 0.400

TRANSITION FIXED

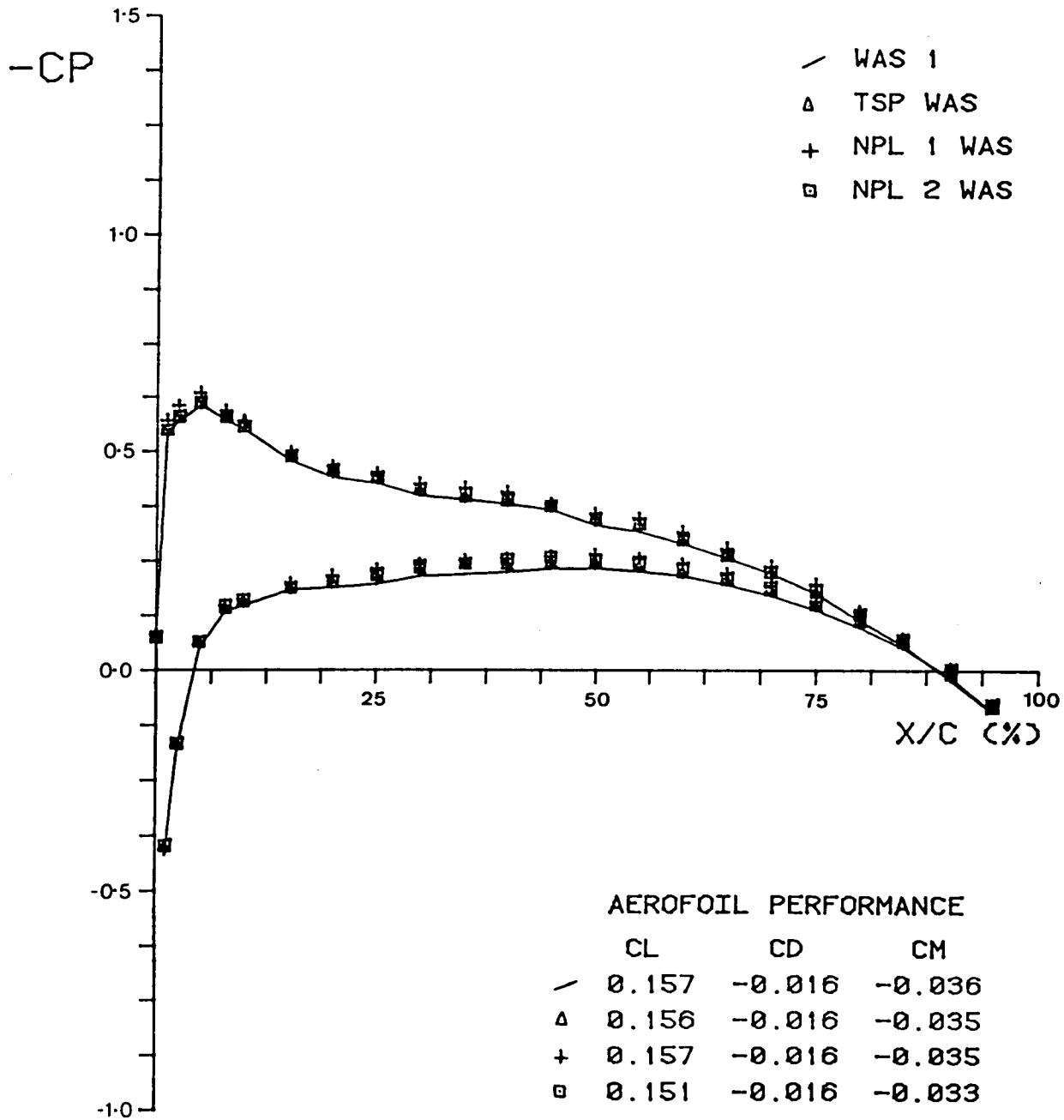


FIG.14.6

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
34 2.0° 0.500

TRANSITION FIXED

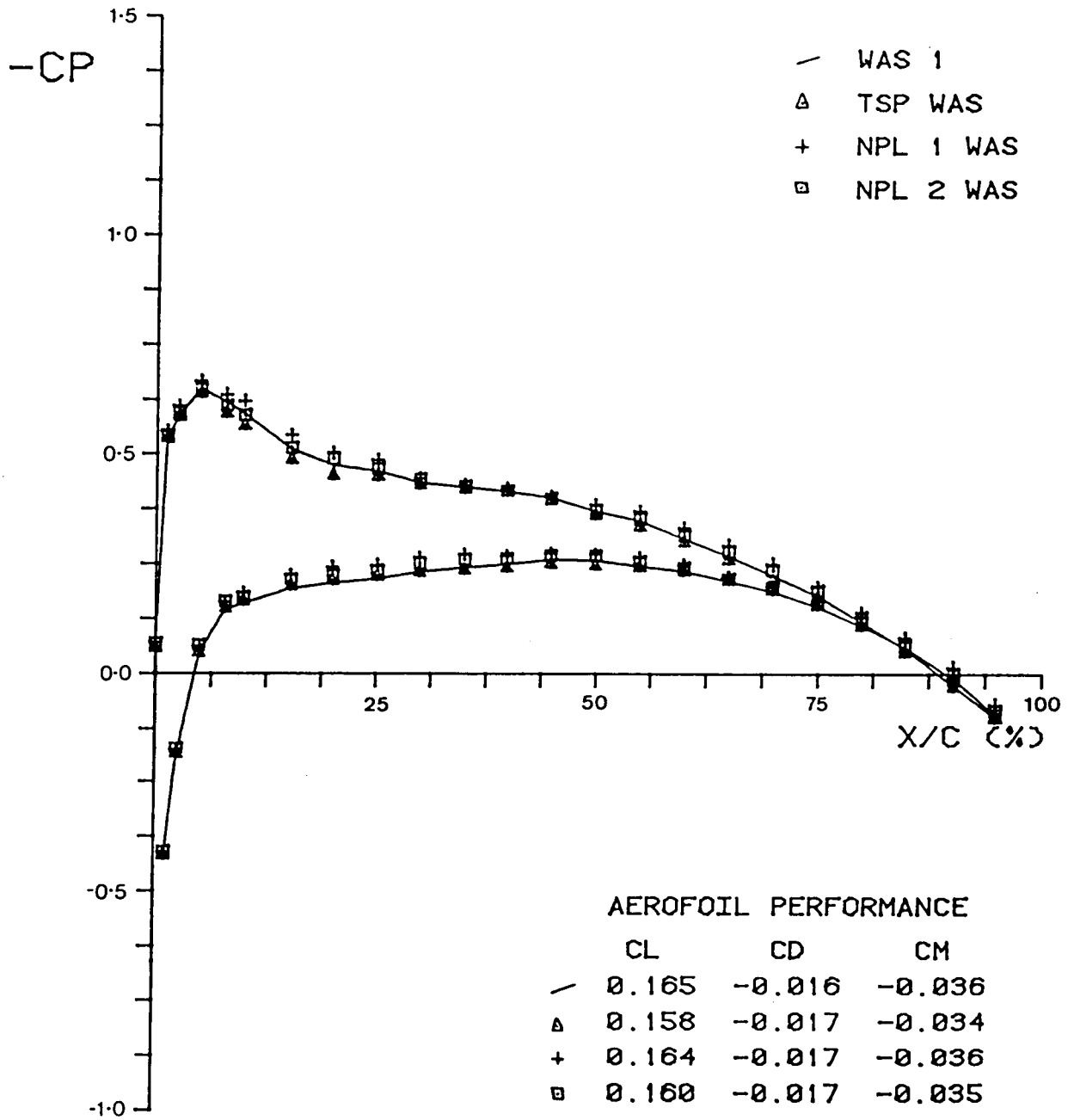


FIG.14.7

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
32 2.0° 0.600

TRANSITION FIXED

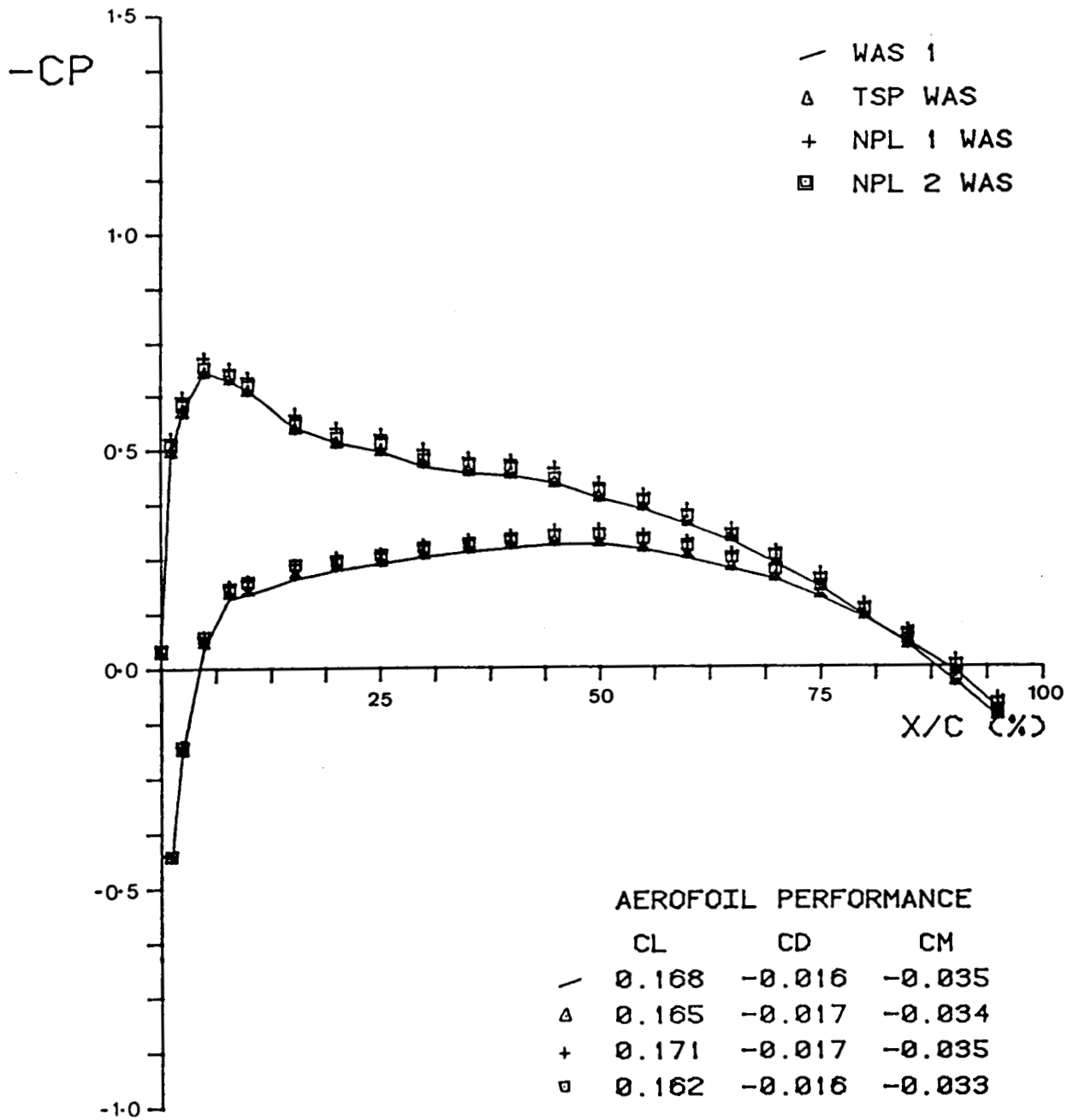


FIG.14.8

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
33 2.0° 0.700

TRANSITION FIXED

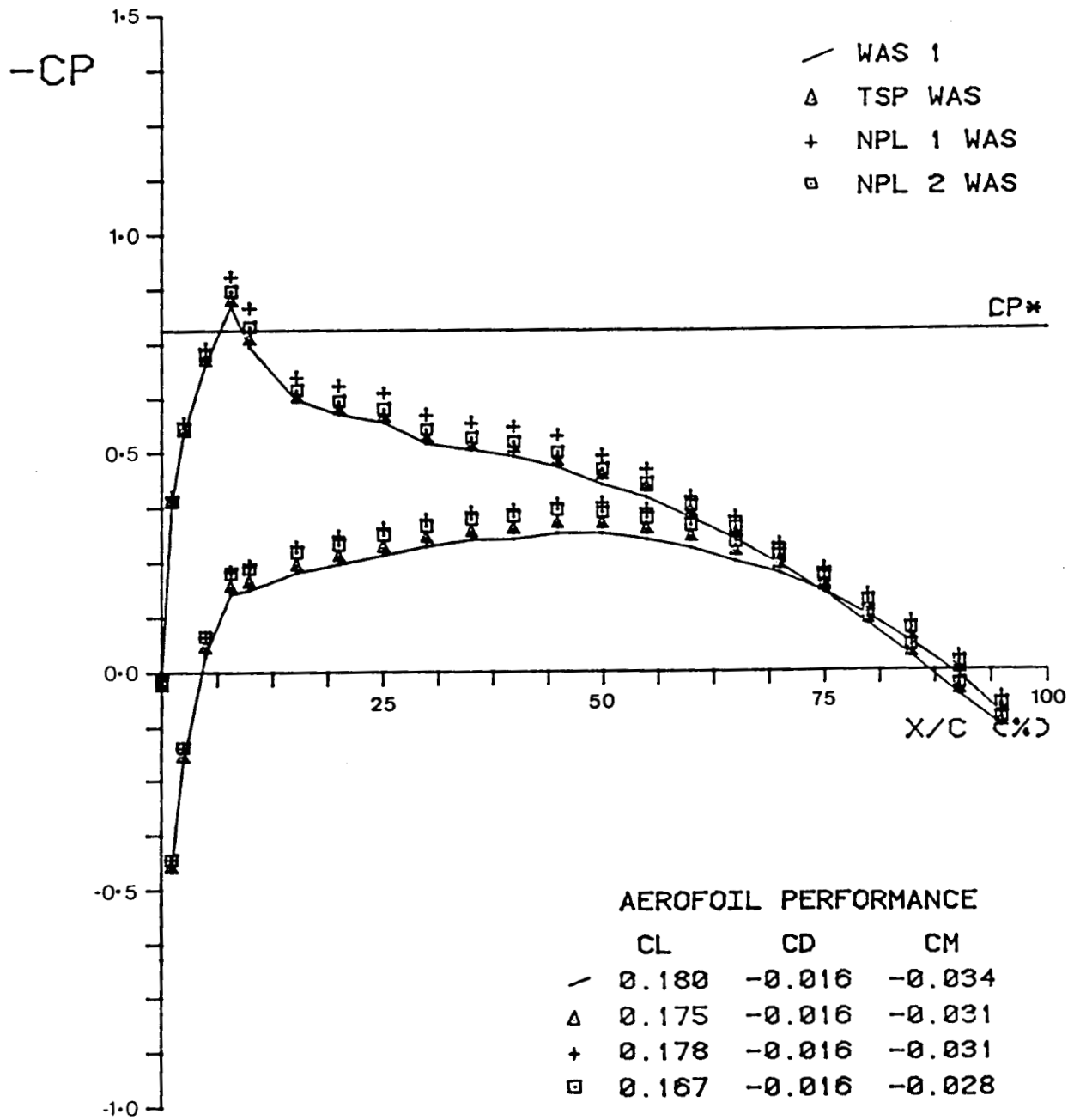


FIG.14.9

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
37 2.0° 0.800

TRANSITION FIXED

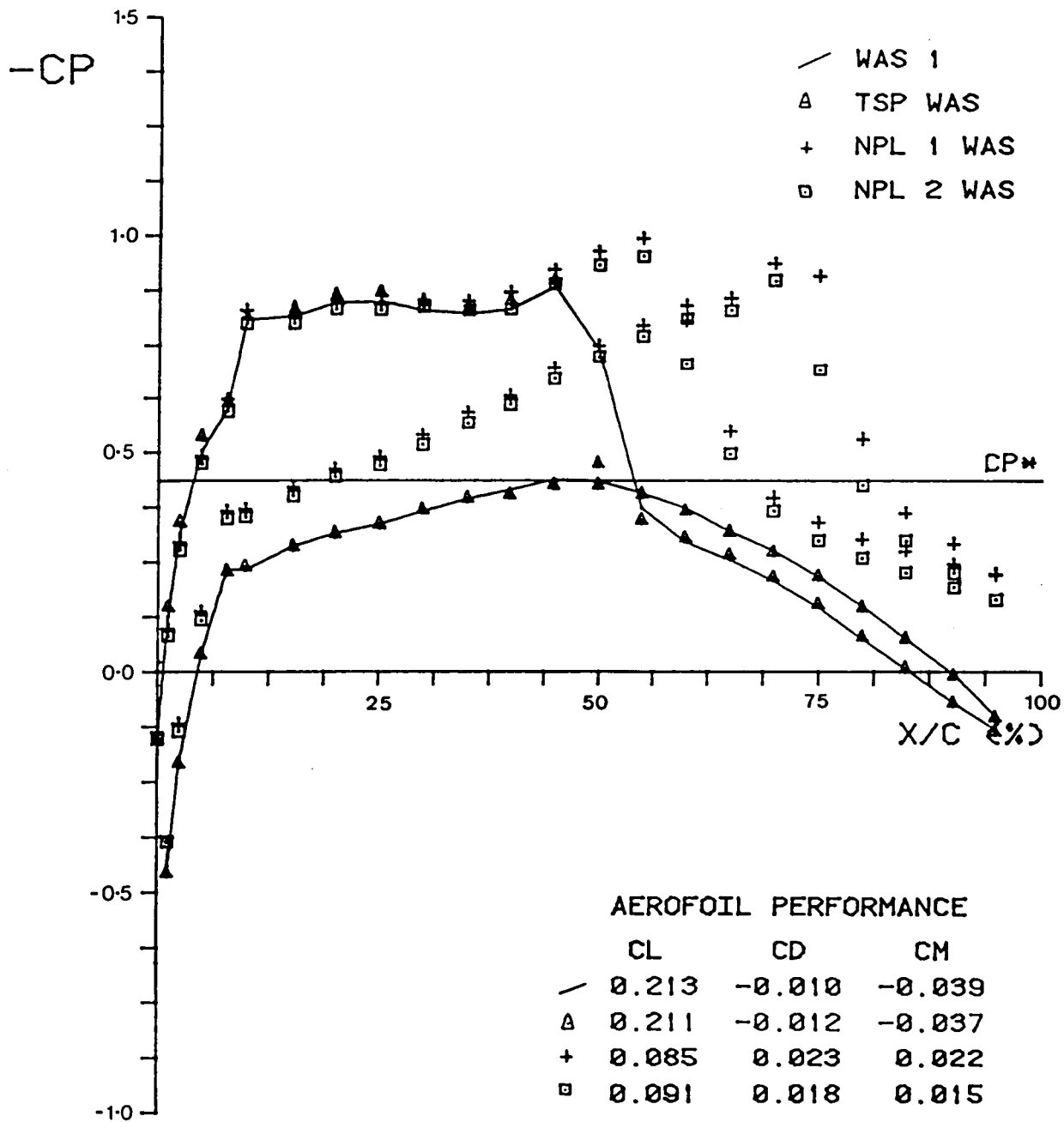


FIG.14.10

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
28 4.0° 0.400

TRANSITION FIXED

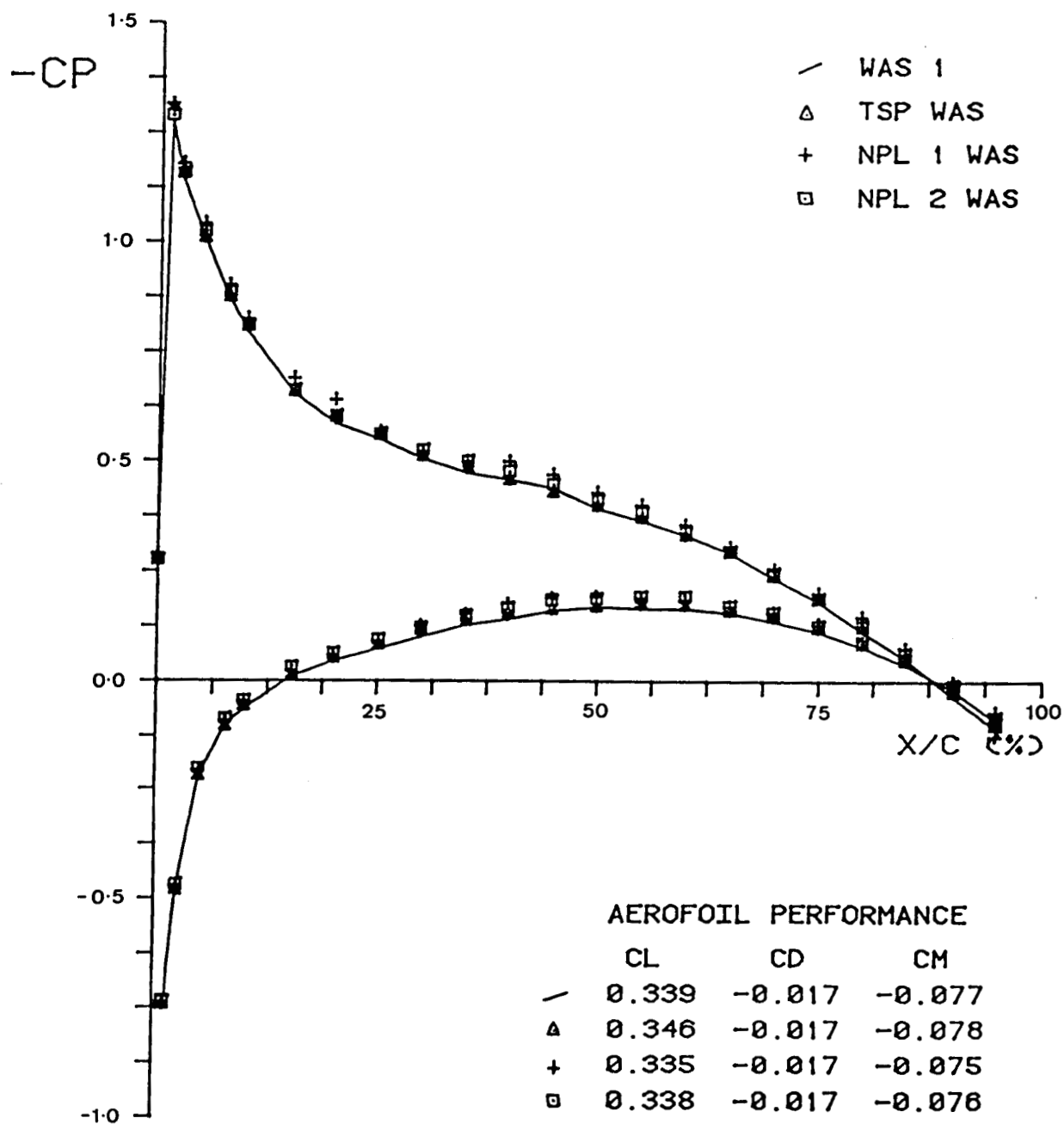


FIG.14.11

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
27 4.0° 0.500

TRANSITION FIXED

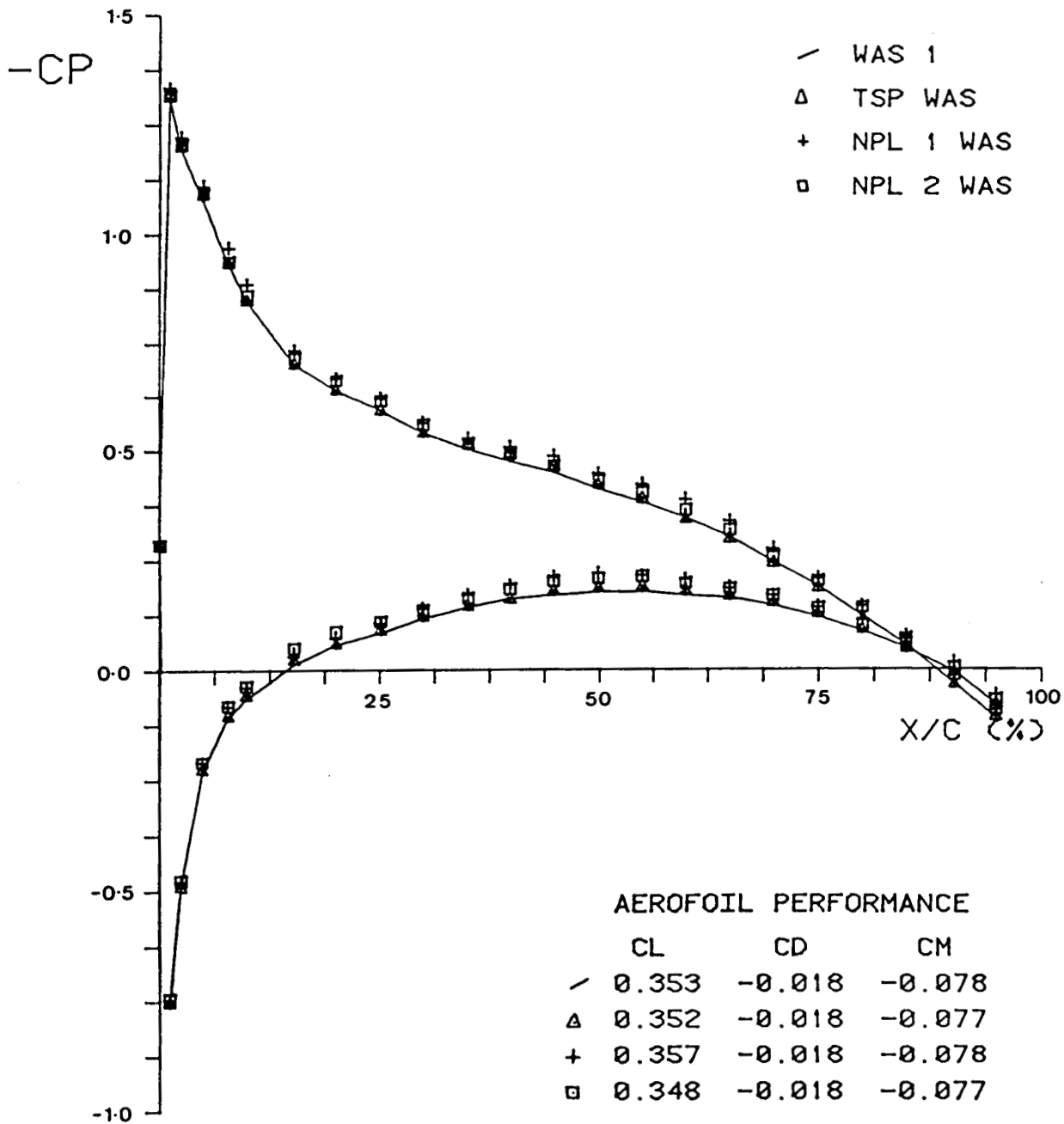


FIG.14.12

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
29 4.0° 0.600

TRANSITION FIXED

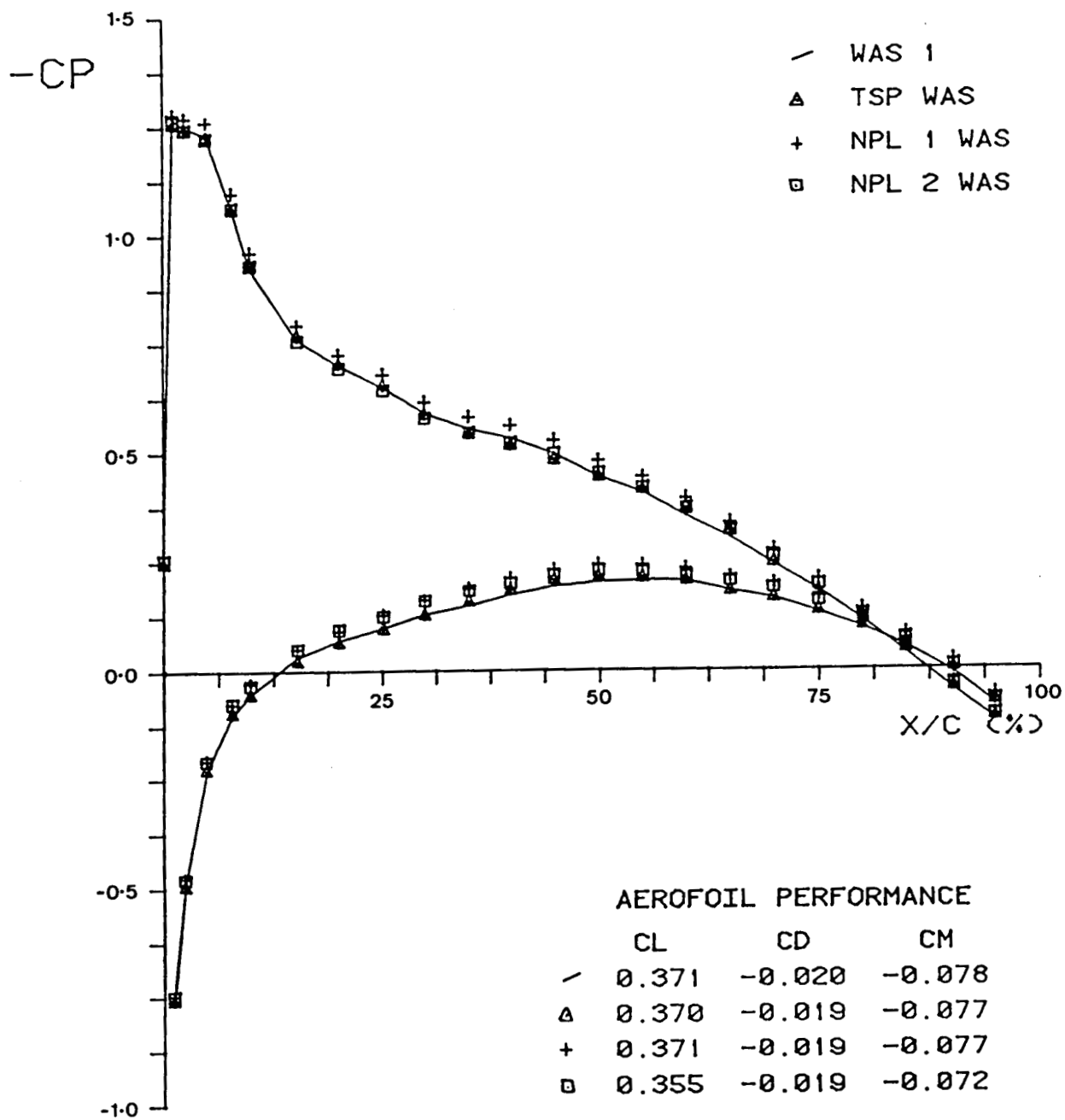


FIG.14.13

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
30 4.0° 0.700

TRANSITION FIXED

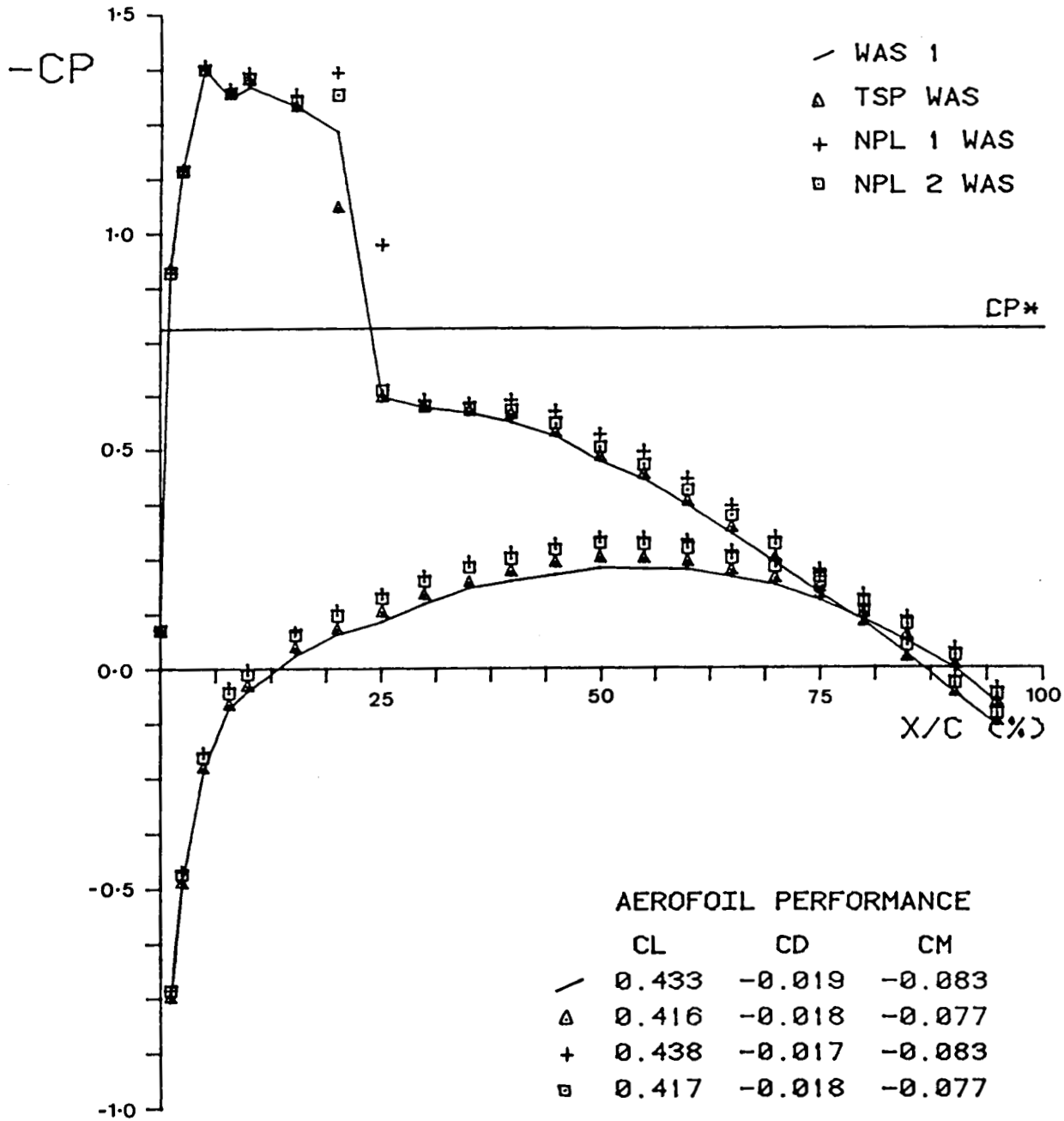


FIG.14.14

FIG.15 SUMMARY OF MODEL FORCE COEFFICIENTS. WALLS SET TO
AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND
STREAMLINED CONTOURS.

Note:- "*STRAIGHT*" refers to aerodynamically straight.

/ WAS 1
 ▲ TSP WAS
 + NPL 1 WAS
 □ NPL 2 WAS
 ○ CONST. PRESS.
 x STRAIGHT

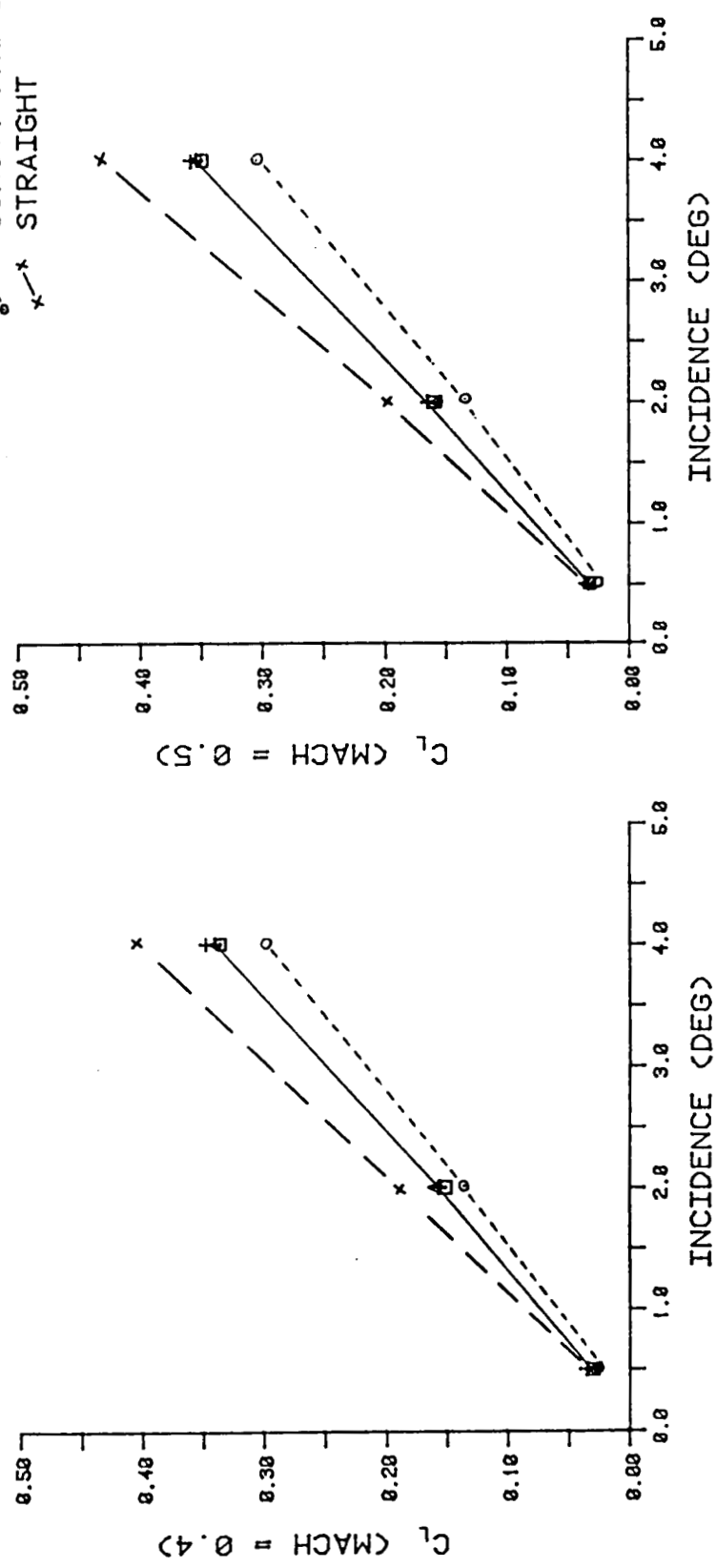


FIG.15.1 NACA 0012-64 SECTION. VARIATION OF LIFT WITH ANGLE OF INCIDENCE. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED CONTOURS ($M_\infty = 0.4$ and 0.5)

/ WAS 1
 ▲ TSP WAS
 + NPL 1 WAS
 □ NPL 2 WAS
 ○ CONST. PRESS.
 × STRAIGHT

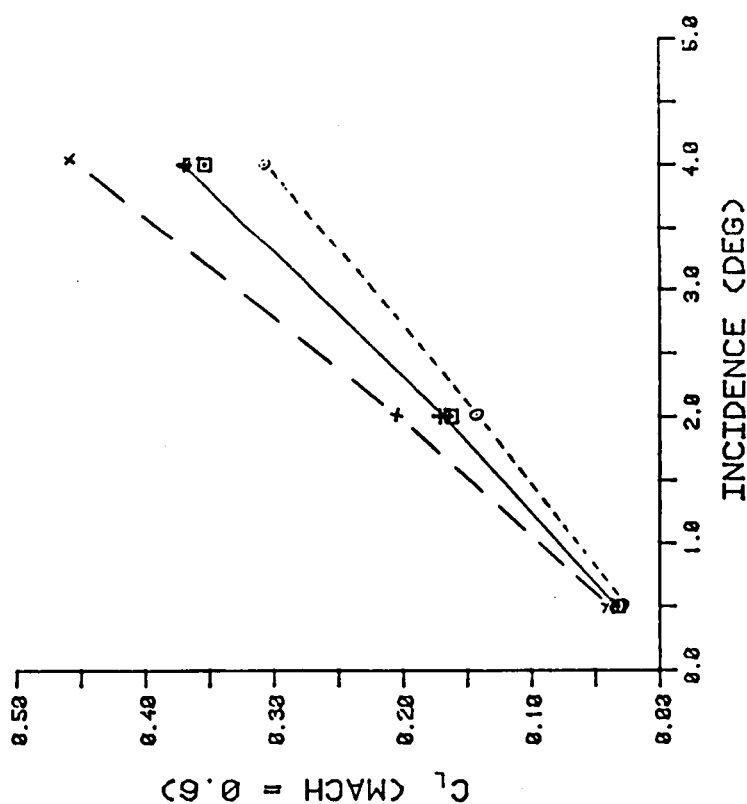
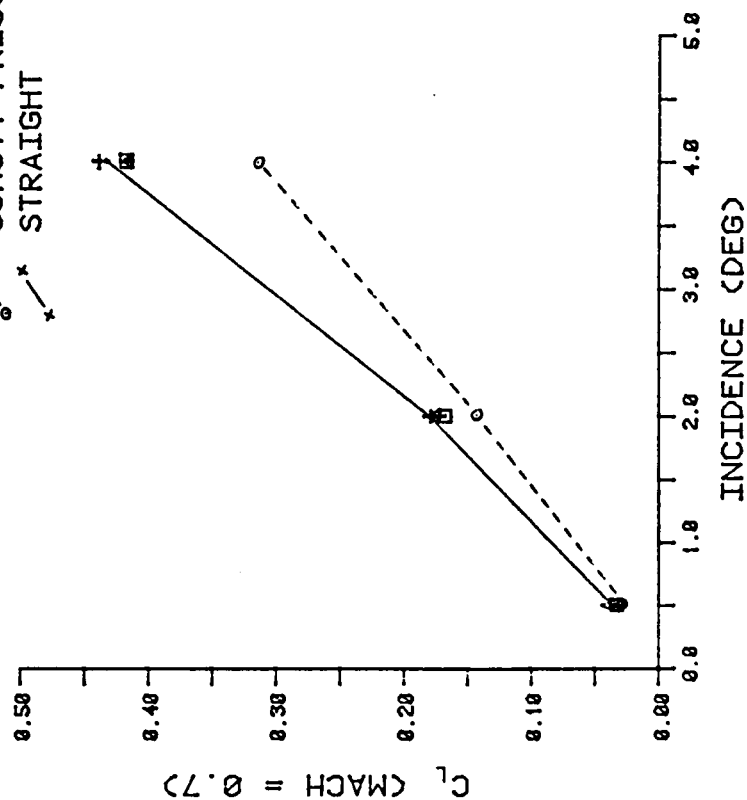


FIG.15.2 NACA 0012-64 SECTION. VARIATION OF LIFT WITH ANGLE OF INCIDENCE. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED CONTOURS ($M_\infty = 0.6$ and 0.7)

/ WAS 1
 ▲ TSP WAS
 + NPL 1 WAS
 □ NPL 2 WAS
 ○ CONST. PRESS.

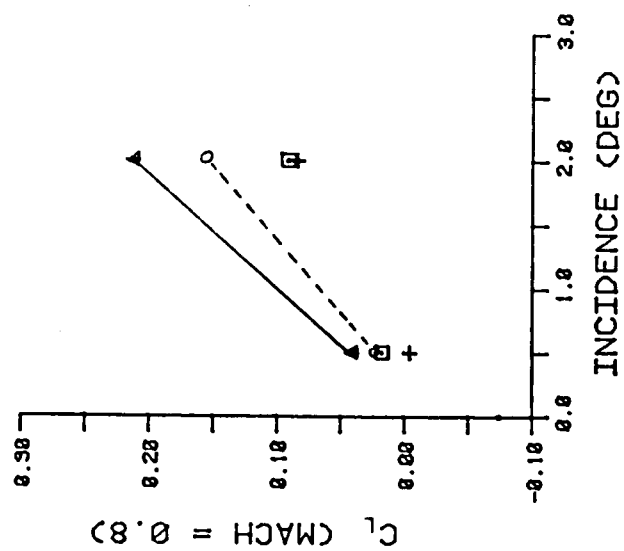
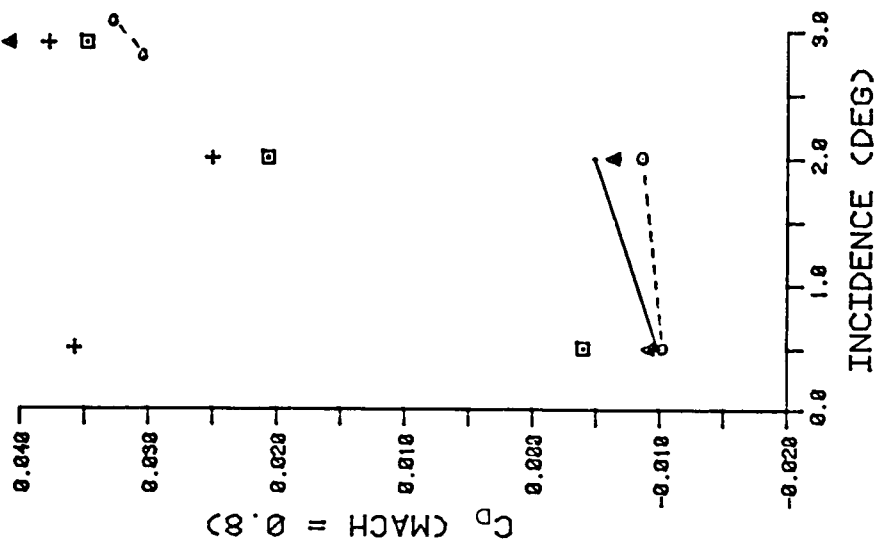


FIG.15.3 NACA 0012-64 SECTION. VARIATION OF LIFT AND FORM DRAG WITH ANGLE OF INCIDENCE. WALLS SET TO CONSTANT PRESSURE AND STREAMLINED CONTOURS ($M_\infty = 0.8$)

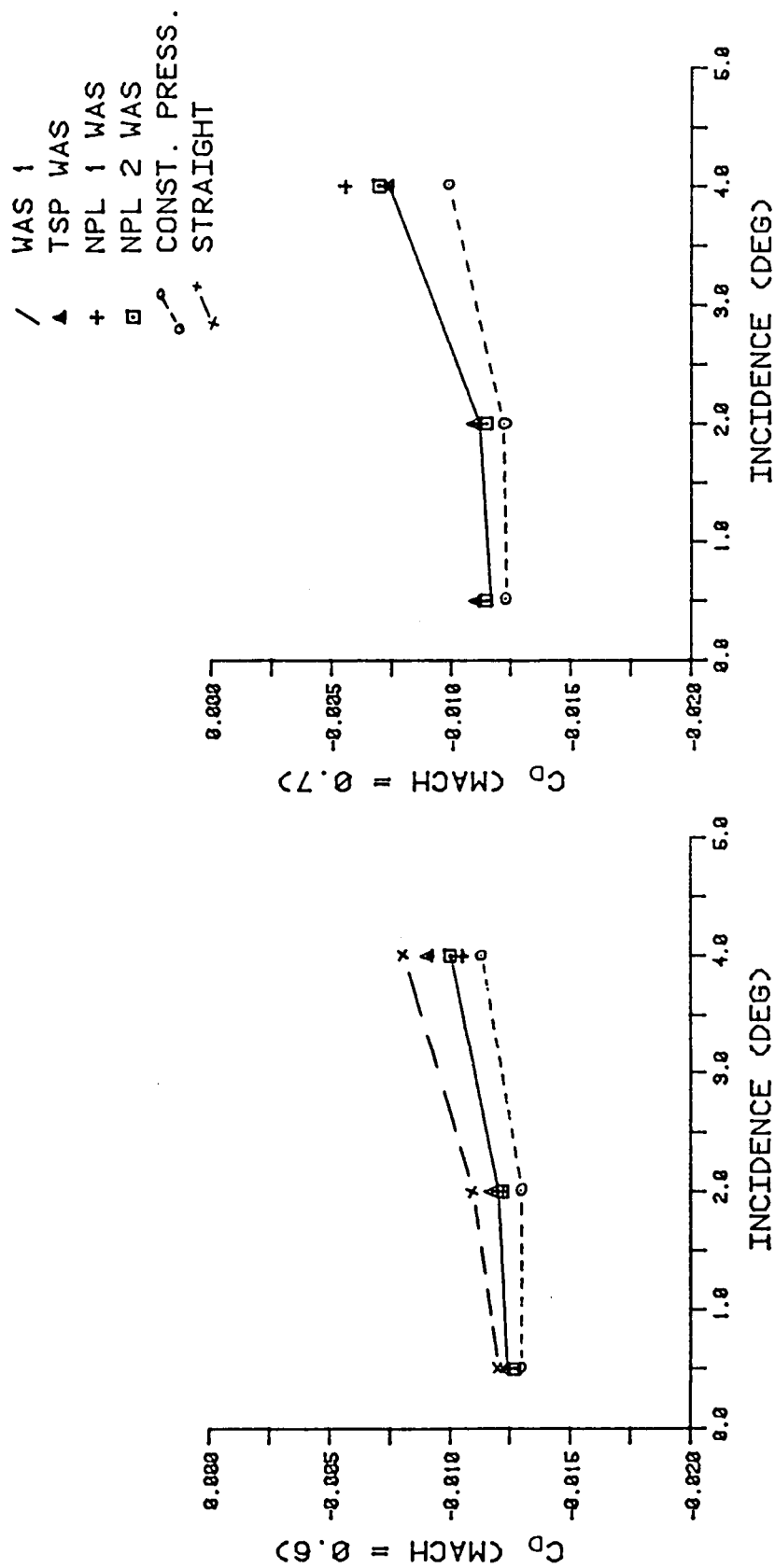


FIG.15.4 NACA 0012-64 SECTION. VARIATION OF FORM DRAG WITH ANGLE OF INCIDENCE. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED CONTOURS ($M_\infty = 0.6$ and 0.7)

/ WAS 1
 ▲ TSP WAS
 + NPL 1 WAS
 □ NPL 2 WAS
 ○ CONST. PRESS.
 x STRAIGHT

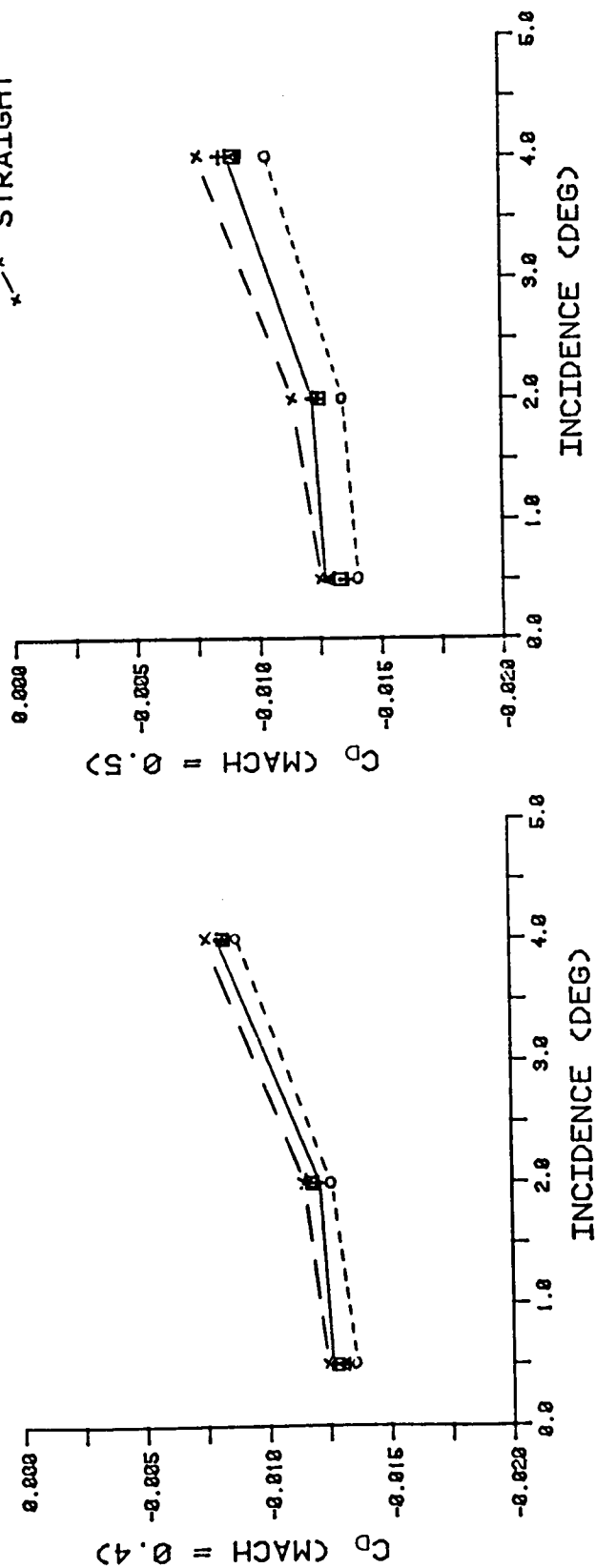


FIG.15.5 NACA 0012-64 SECTION. VARIATION OF FORM DRAG WITH ANGLE OF INCIDENCE. WALLS SET TO AERODYNAMICALLY STRAIGHT, CONSTANT PRESSURE AND STREAMLINED CONTOURS ($M_\infty = 0.4$ and 0.5)

/ WAS 1
 ▲ TSP WAS
 + NPL 1 WAS
 □ NPL 2 WAS

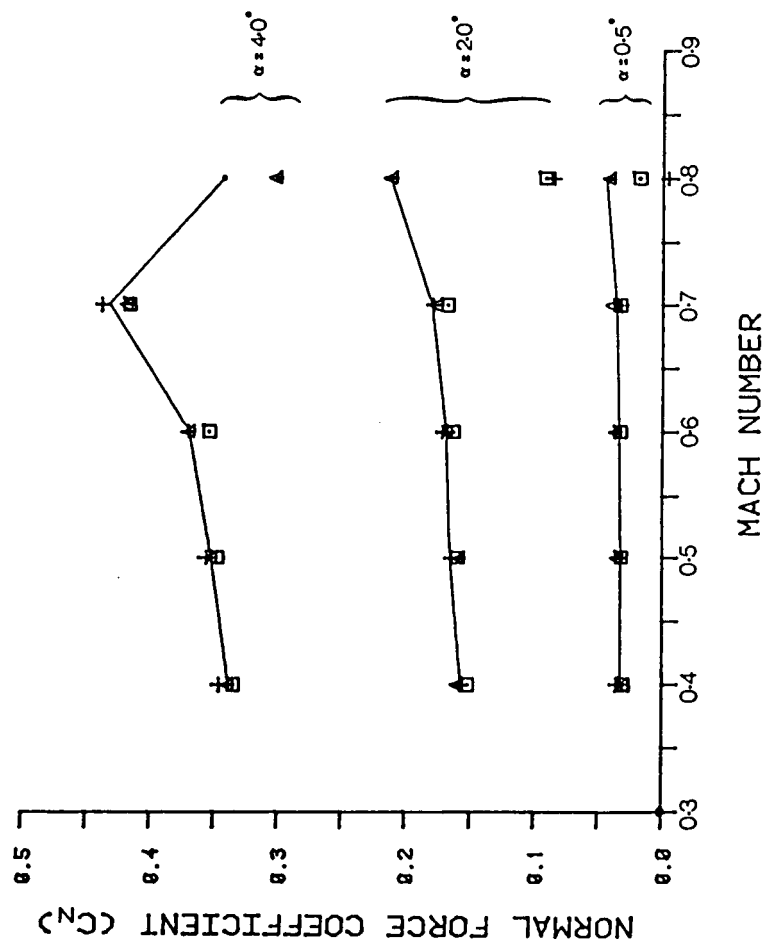
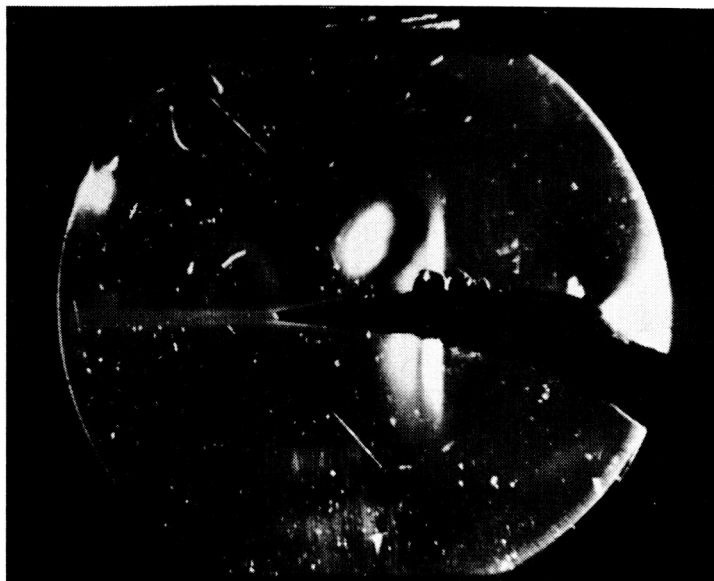


FIG.16 NACA 0012-64 SECTION. VARIATION OF NORMAL FORCE COEFFICIENT WITH MACH NUMBER. WALLS STREAMLINED

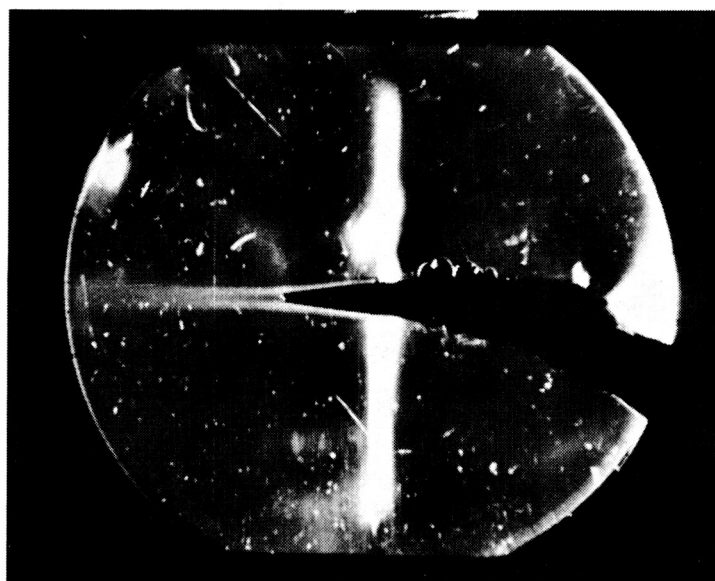
ORIGINAL PAGE IS
OF POOR QUALITY.

NACA 0012-64 SECTION

$M_{\infty} = 0.8$; $\alpha = 0.5^{\circ}$



WAS 1



NPL 2 WAS

FIG. 17 SCHLIEREN PICTURES ILLUSTRATING THE BREAK-
DOWN OF NPL WAS

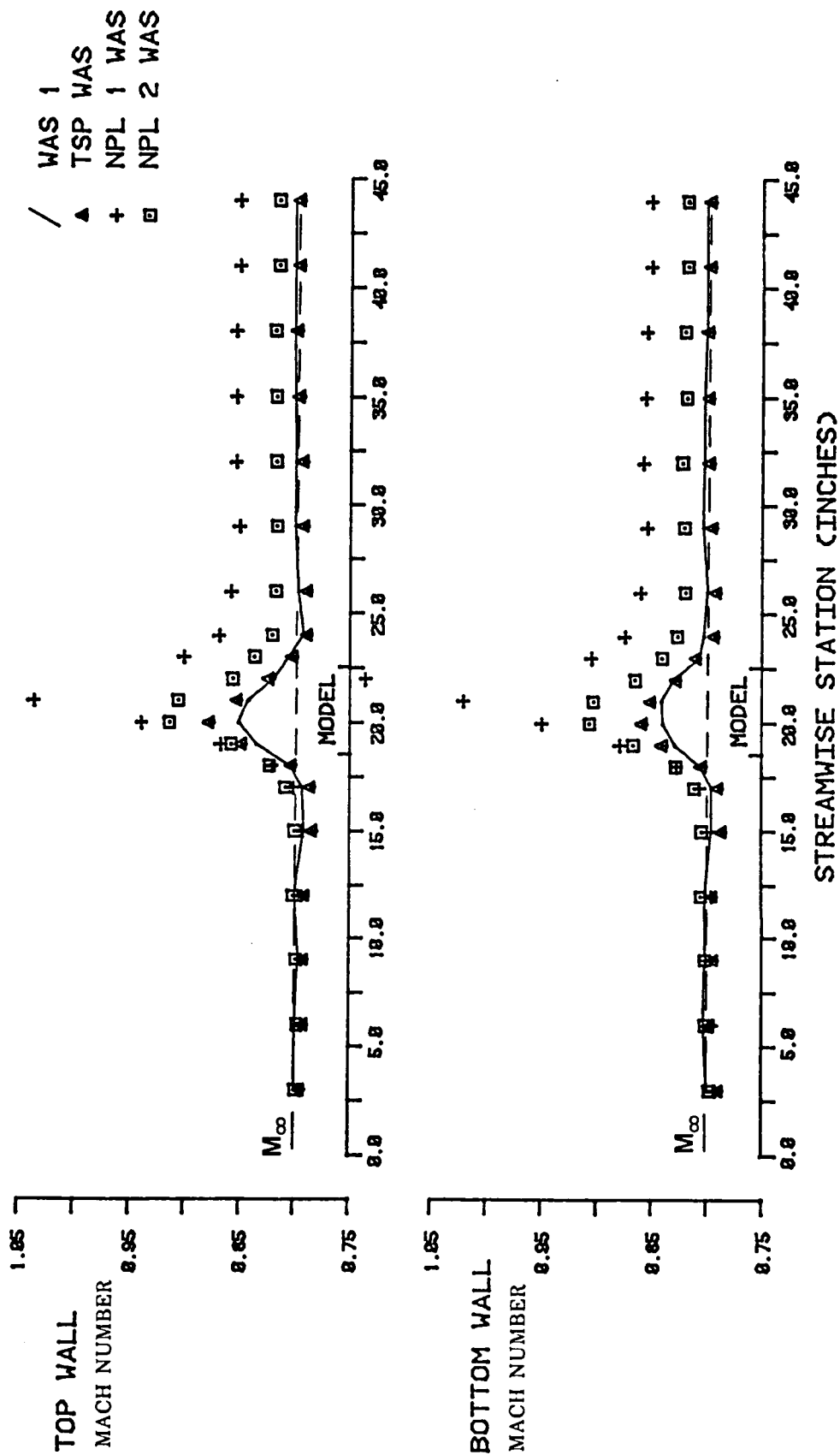


FIG.18 NACA 0012-64 MEASUREMENTS ($M_\infty = 0.8$, $\alpha \approx 0.5^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF STREAMLINED CONTOURS

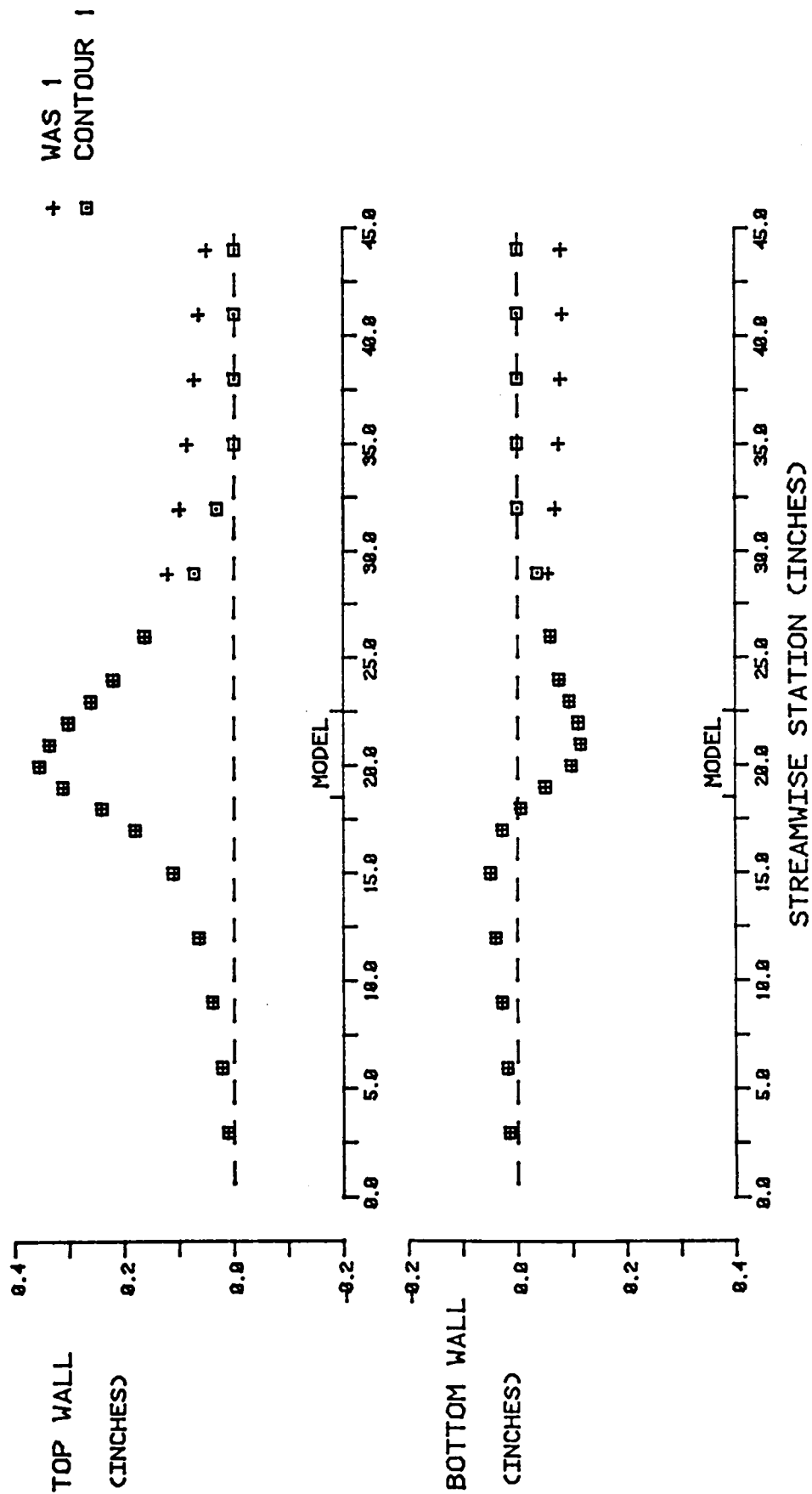


FIG.19.1 WAKE PINCH TESTS:- NACA 0012-64 MEASUREMENTS ($M_\infty = 0.8$; $\alpha = 6.0^\circ$). DISPLACEMENTS OF WALLS FROM AERODYNAMICALLY STRAIGHT CONTOURS. WALLS SET TO WAKE PINCH TEST CONTOURS

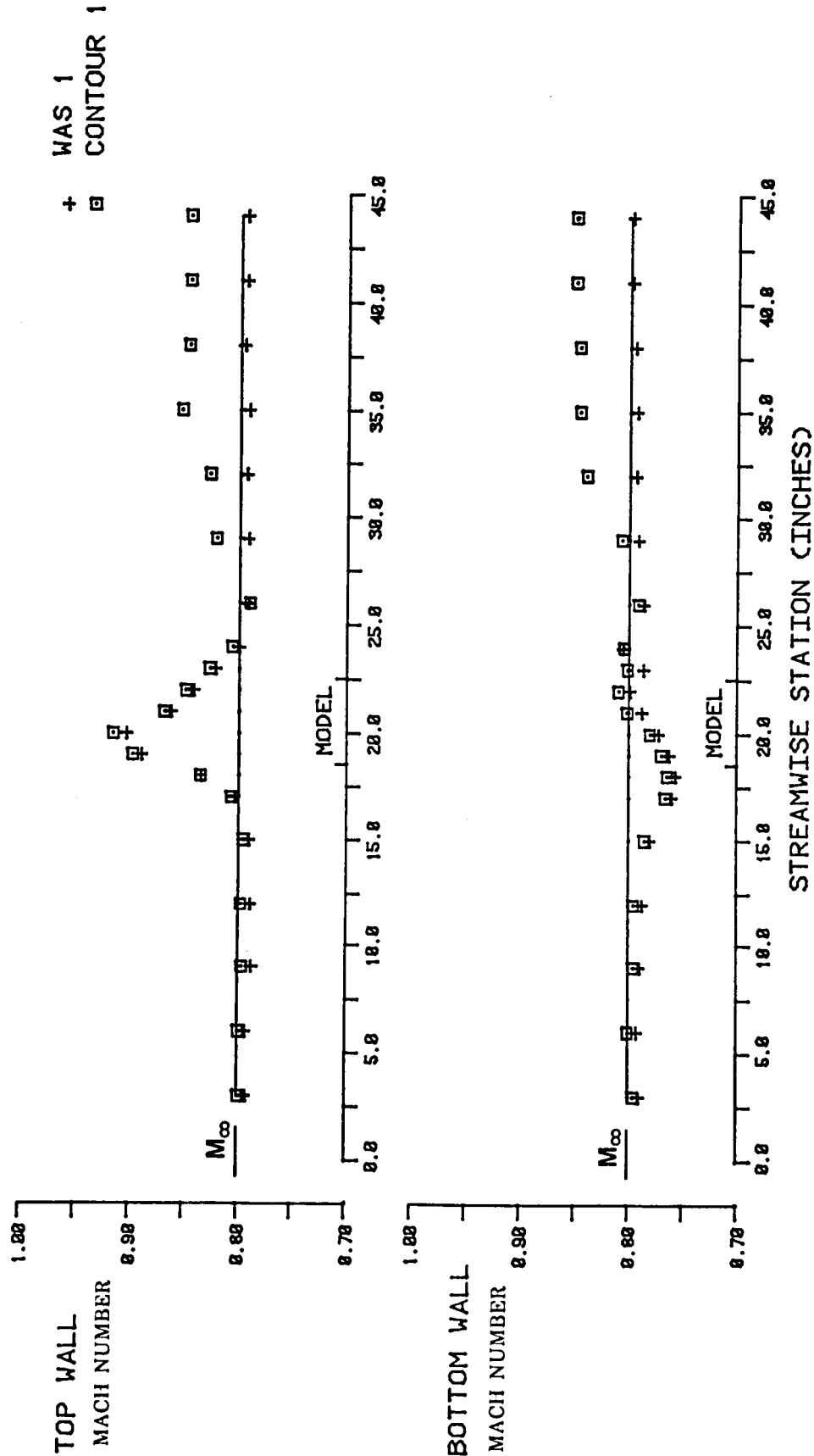


FIG.19.2 WAKE PINCH TESTS:- NACA 0012-64 MEASUREMENTS ($M_\infty = 0.8$; $\alpha \approx 6.0^\circ$). DISTRIBUTIONS OF MACH NUMBER ALONG CENTRELINES OF WALLS SET TO WAKE PINCH TEST CONTOURS

NACA 0012-64 SECTION

RUN NO ALPHA MACH NO
4 6.0° 0.800

TRANSITION FIXED

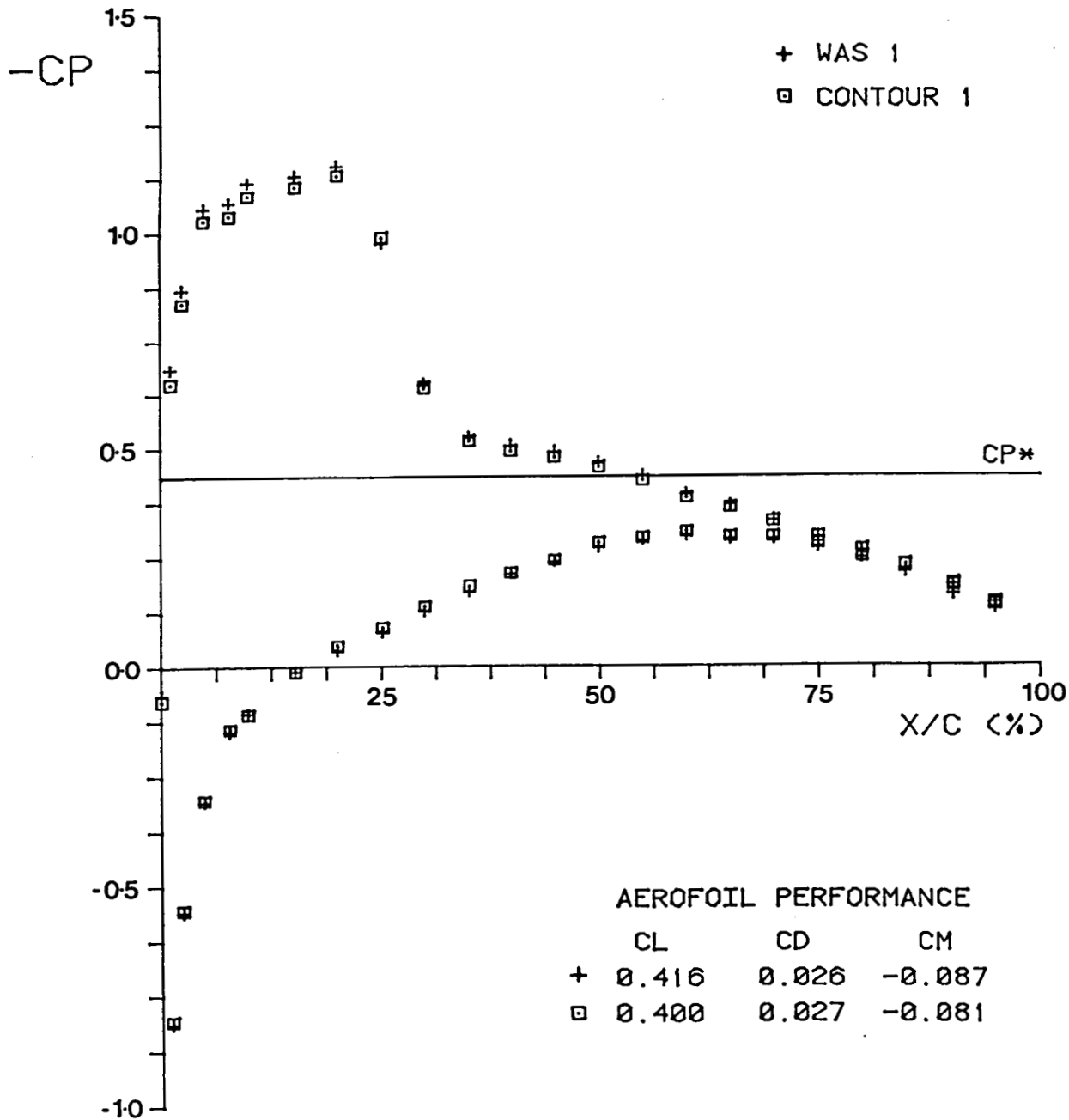


FIG.19.3 WAKE PINCH TESTS:- MODEL PRESSURE DISTRIBUTIONS. WALLS SET TO WAKE PINCH TEST CONTOURS



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16. Abstract The first documented wind tunnel employing a flexible walled test section for the purpose of eliminating wall interference was constructed in England by the National Physical Laboratory (NPL) during the late 1930's. The tunnel was transonic and designed for two-dimensional testing. In an attempt to eliminate the top and bottom wall interference effects on the model NPL developed a strategy to adjust two flexible walls to streamlined shapes. This report covers an evaluation of the NPL wall adjustment strategy in a modern wind tunnel; namely the Transonic Self-Streamlining Wind Tunnel (TSWT) at the University of Southampton, England. The evaluation took the form of performance comparisons with other modern strategies which have been developed for use in, and proven in, the TSWT.					
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